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Coupling Calculation and Analysis of Harmonic Propagation in Wind Farm

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***Abstract*—Because the doubly-fed wind turbine contains a large number of power electronic equipment, as well as the randomness and uncontrollability of wind power generation, the wind farm inputs a large amount of harmonics while inputting active power to the grid, which brings many adverse effects to the power system. Therefore, analyzing the harmonic content of wind turbines to the main busbar of the grid is a key issue in the development of the wind power industry. The research object of this paper is mainly the harmonic propagation and coupling of the wind farm composed of doubly-fed wind turbines. By changing the wind speed and the number of wind turbines, and analyzing the harmonics by FFT (Fast Fourier Transform). The total distortion rate of the wave summarizes the variation law of the internal harmonic distortion rate of the wind farm with the number of wind turbines and the operating state.**

Keywords—doubly-fed wind turbine; wind farm; harmonic coupling; fast fourier transform

I. Introduction

With the growth of wind farm capacity and the rapid development of power electronics technology, the impact of harmonics on wind farms has become a problem that cannot be ignored. At present, the power quality problem caused by the integration of large-scale wind farms has become an unstable factor in the quality of wind power.

In recent years, China's wind power installed capacity has been increasing, and there are many documents in the country to describe it. The literature [1] analyzes four wind farm models and proposes the concept and necessity of wind farm connection-dynamic process modeling. The literature [2] outlines the modeling of doubly-fed wind turbines and direct-drive permanent magnet synchronous fans. The method of calculating the energy of wind farms is introduced. In addition, the research needs and trends of wind farm equivalent modeling are also concerned. The literature [3] summarizes the statistical status of wind farm equilibrium research and clustering parameters. The literature [4] construct a constant model of MATLAB /Simulink constant frequency and periodic constant frequency, compare the operation process of two fans in the dynamic process.

The harmonics generated by the wind turbine are mainly related to the operation mode of the unit and the operation mode of the unit. Domestic and foreign scholars have done a lot of research on the harmonics of wind power generation. The literature [5] simulates the rotor-side transducer of the doubly-fed wind turbine, and proves that the harmonic content of the doubly-fed motor is minimized when synthesized by the modulation method. The literature [6] mainly proposes the mixing model to study the diffusion of different types of harmonics in wind turbines. The literature [7] concludes that the harmonic resonance frequency is about 1.1 kHz through the wind power harmonic test, and proposes an effective harnessing scheme for harmonics in wind farm. The literature [8] provides an effective solution to the sudden and random nature of harmonics in wind farms by showing the method of predicting harmonic currents.

This paper summarizes the analysis methods commonly used for different types of harmonics, and chooses the discrete Fourier series method to calculate the harmonic propagation in wind farms. The wind farm with doubly-fed wind turbines was modeled by MATLAB /Simulink simulation software, and the internal harmonic waveform of wind farm was simulated. The variation law of internal harmonics of wind farm was summarized. In the grid-connected state, the wind farm with single, two, and multiple doubly-fed wind turbines is simulated. The harmonics inside the three types of wind farms are analyzed and compared by simulation data. The number of wind motors in the field increases, and the total distortion rate of harmonics in the wind farm decreases.

II. Research on Harmonic Modeling of Double-fed Wind Farm

A. Basic Definition of Harmonics

Harmonic wave refers to the electric quantity contained in the current in a strict sense. It is an integral multiple of the fundamental wave. Generally refers to the Fourier series decomposition of the periodic non-sinusoidal electric quantity. The remaining amount of electricity generated by the current greater than the fundamental frequency. Broadly speaking, since the effective component of the AC grid is a single frequency of the power frequency, any component that is different from the power frequency can be called a harmonic.

The main causes of harmonics are the sinusoidal voltage is pressed to the nonlinear load, the fundamental current is distorted to generate harmonics. And the main non-linear loads are UPS, switching power supply, rectifier, inverter, inverter and so on.

The harmonics of the power grid are mainly caused by three aspects: power generation equipment (power supply end), power transmission and distribution equipment, and non-linear load of power system. The total harmonic distortion rate is expressed as follow.

$$THD = \sqrt{\frac{\sum_{i=2}^{\infty} I_i^2}{I_1^2}} \quad (1)$$

B. Harmonic Modeling of Doubly-fed Wind Turbine

In the power system, the power grid is ideally receiving a constant frequency of electric energy. But due to the existence of non-linear loads in the power system, the voltage and current output by the power system are not ideal co-frequency sine waves. And there will be certain distortion.

Due to the large-scale use of power electronic devices in the field of wind power, especially for doubly-fed wind turbines, which contain a large number of power electronic devices, harmonics are inevitably generated. There are two main sources of harmonics in the doubly-fed wind turbine.

First, the tooth harmonics generated by the stator. They are also called the inherent harmonics of the fan. And the generation of harmonics is determined by the design of the wind turbine. The frequency of the tooth harmonic is calculated as shown in Equation 2.

$$f_{sh} = f_1[\frac{2S}{N_p}(1-s) \pm 1] \quad (2)$$

Where f_{sh} represents the frequency of the tooth harmonic and s represents the number of slots of the motor stator. The switching harmonics generated by the switching device at the converter are calculated as shown in Equation 3.

$$f_{sh} = \mathrm{N}f_2 \pm \mathrm{J}f_2 \quad (3)$$

Where N represents the carrier rate and f_2 represents the frequency of the electron current. N = 2, 4, 6, ...

Second, the loss of transformers and transmission lines will also produce a certain degree of harmonics.

III. Harmonic Analysis of Doubly Fed Wind Farm

The wind farm model is established with MATLAB /Simulink. The rated wind speed of the doubly-fed fan model is 11m/s. The waveforms of sub-synchronization (8m/s) and super-synchronization (15m/s) can be observed when the simulated wind speed is different. variety.

The wind farm model frequency is 50 Hz. The stator side voltage is AC 690V, the medium voltage grid side voltage is 35kV, and the high voltage grid side voltage is 220kV. Changing the internal parameters of the doubly-fed wind turbine can change the number of units. Through the Sequence Analyzer module, the amplitude variation waveform of each harmonic current can be observed by adjusting the harmonic order of the internal parameters. This article only observes the odd harmonic waveforms of 3rd, 5th, 7th, and 9th as shown in Figure 1.

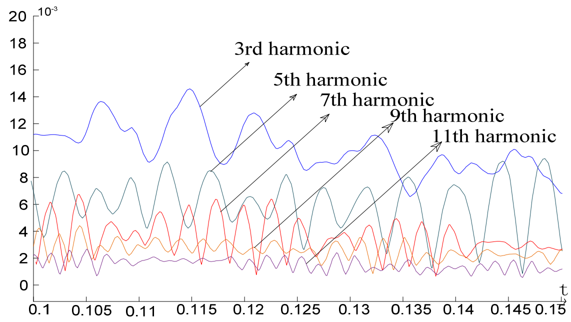

FIGURE I. WAVEFORM OF EACH HARMONIC

Among them, the top five colors correspond to the waveforms of the 3rd, 5th, 7th and 9th harmonics. It can be seen from the waveform that the content of the third harmonic is much larger than other high harmonics. The amplitude attenuation amplitude of the harmonic gradually decreases with the increase of the harmonic order and the harmonic content gradually decreases with the increase of the number of times. In addition, by superimposing the harmonics, the overall trend of harmonics over time can be observed. The effective value and phase of the all harmonics are selected for superposition. The superposition effect is shown in Figure 2.

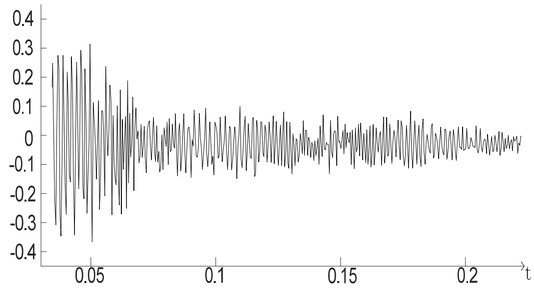

FIGURE II. HARMONIC SUPERPOSITION EFFECT DIAGRAM

IV. Harmonic Analysis of Doubly Fed Wind Farm

In the MATLAB environment, the parameters inside the wind farm are adjusted. The harmonics of the wind turbine 690V bus side, 35kV bus side and 220kV bus side are analyzed under different conditions. By changing the number of fans in the wind farm, the ten-cycle current waveform at 0.02s is selected to observe the variation of harmonic coupling in the wind farm. Analysis of Harmonic Characteristics of Doubly-fed Wind Farm Group.

A. Harmonic Analysis of Single-fed Wind Turbine Generators Connected to the Grid

Firstly, the harmonics of a single fan in the sub-synchronous and super-synchronous state are compared. The FFT analysis is applied to the three-phase currents of the 690V bus side, the 35kV bus side, and the 220kV bus side for the wind speeds of 8m/s and 15m/s. The THD (Total Harmonic Distortion) is used as an indicator to reflect the degree to which the sinusoidal current is affected by harmonics. The simulation results are shown in the following figure 3.

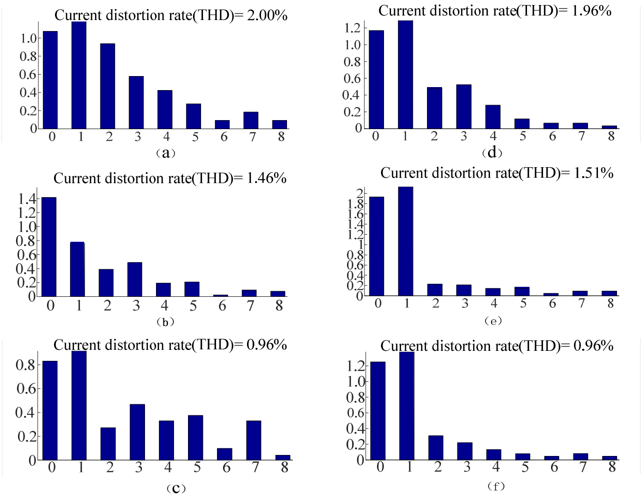

FIGURE III. BUS SIDE HARMONIC ANALYSIS RESULT

Draw Table 1 and Table 2 to summarize the harmonic distortion rate and harmonic content of different busbars.

TABLE I. DIFFERENT BUSBAR CURRENT HARMONIC DISTORTION RATE IN SUB-SYNCHRONOUS STATE

Measuring bus	690V	35kV	110kV
THD	2.00%	1.46%	0.96%
Third harmonic	0.71%	0.50%	0.28%
Fifth harmonic	0.53%	0.37%	0.21%
Seventh harmonic	0.47%	0.39%	0.25%

TABLE II. DIFFERENT BUSBAR CURRENT HARMONIC DISTORTION RATE IN SUPER-SYNCHRONOUS STATE

Measuring bus	690V	35kV	110kV
THD	1.96%	1.51%	0.96%
Third harmonic	0.57%	0.36%	0.23%
Fifth harmonic	0.37%	0.20%	0.13%
Seventh harmonic	0.12%	0.15%	0.15%

From the analysis results in Table 1 and Table 2, we can see the measurement data of different bus-side current distortion rates for a single fan by changing its wind speed. The 690V bus-side current harmonic distortion rate is the largest, followed by the 35kV bus side, 220kV bus. The side harmonic distortion rate is the smallest. It can be seen that the three-phase current of the single wind turbine is gradually stabilized from the 690V bus side to the 220kV bus side, and the harmonic distortion rate is reduced. For a single fan with different wind speeds, the 690V bus side and the 35kV bus side are super-synchronized. The harmonic distortion rate of the sub-synchronous fan is slightly reduced.

B. Harmonic Analysis of Multiple Doubly-fed Wind Turbines Connected to the Grid

The grid-connected model of multiple doubly-fed wind turbines is the same as the grid-connected model of two doubly-fed wind turbines, and only needs to change the parameters of the wind turbine. Similar to the analysis method of the previous chapter, this set of 20 wind turbines in the wind farm first analyzes 5 sub-synchronous generation wind speeds at 8m/s and 15 super-synchronous generation wind speeds in parallel at 15m/s, respectively for 690V busbars. Harmonic current analysis is performed on the side, 35kV bus side and 220kV bus side. The simulation results are shown in the figure 4.

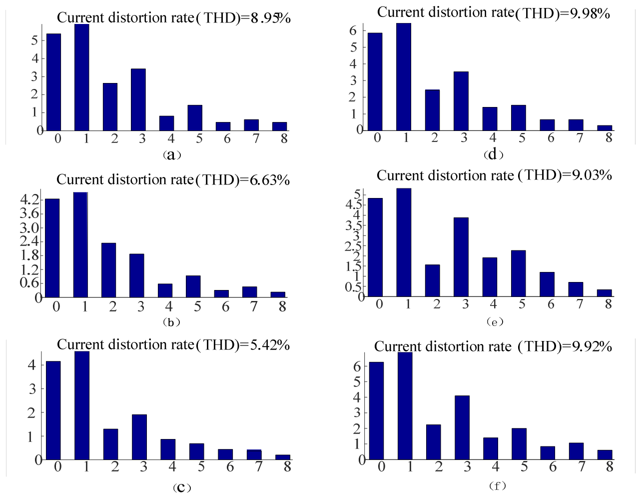

FIGURE IV. BUS SIDE HARMONIC ANALYSIS RESULT

Draw Table 3 and Table 4 to summarize the harmonic distortion rate and harmonic content of different busbars.

TABLE III. DIFFERENT BUSBAR CURRENT HARMONIC DISTORTION RATE IN SUB-SYNCHRONOUS STATE

Measuring bus	690V	35kV	110kV
THD	8.95%	6.63%	5.42%
Third harmonic	3.10%	2.20%	1.20%
Fifth harmonic	1.80%	1.60%	0.60%
Seventh harmonic	1.90%	1.90%	0.80%

TABLE IV. DIFFERENT BUSBAR CURRENT HARMONIC DISTORTION RATE IN SUPER-SYNCHRONOUS STATE

Measuring bus	690V	35kV	110kV
THD	9.98%	9.03%	9.92%
Third harmonic	4.50%	3.70%	3.90%
Fifth harmonic	2.30%	1.40%	1.30%
Seventh harmonic	0.80%	0.80%	2.20%

From the analysis results in Table 3 and Table 4, it can be seen that when the number of sub-synchronous wind turbines is higher than the number of super-synchronous wind turbines. The harmonic distortion rate of each side is improved, indicating that there are many sub-systems in the wind farm for a long time. Synchronously operating wind turbines can adversely affect the electrical energy of the wind farm. However, the harmonic distortion rate of the two wind turbines is still lower, indicating that the harmonic currents still have mutual coupling.

V. CONCLUSION

In this chapter, the wind farm with single and multiple doubly-fed wind turbines is modeled and simulated. The influence of the number of wind turbines and the running state of wind turbines (wind speed) on the current harmonics of each side is analyzed by FFT in conclusion.

(1) The current harmonic distortion rate is low when a single doubly-fed fan is running, the time for the three-phase current to reach the steady state is short, the harmonic distortion rate of the 690V bus side is the largest, and the ratio of the wind turbine in the sub-synchronous state is higher. The current harmonic content of the super-synchronized wind turbine increases.

(2) When multiple doubly-fed wind turbines are running, the harmonic currents of multiple harmonic sources are coupled, which will significantly reduce the harmonic content compared with that of two doubly-fed wind turbines, i.e. produce mutual cancellation. However, the harmonic content of doubly fed wind turbines is higher than that of single doubly fed wind turbines. When multiple doubly-fed fans operate, the harmonic content of the fan side is higher, and the more the number of wind turbines in sub-synchronous operation, the greater the harmonic distortion rate, which will have a negative impact on the wind farm.

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