Wind Farm Harmonic Impedance Estimation Based on Stochastic Subspace Method

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Abstract. Wind farm harmonic impedance is important parameter of wind farm. It has an important influence on stability calculation, stability analysis and stability assessment. To solve this problem that wind farm harmonic impedance is considered as static parameter, an assessment method of wind farm harmonic impedance based on output-error model parameter estimation is proposed. A simplified treatment for the wind farm PCC model is made. The simplified model is transformed into two-node equivalent model. And then the amplitude-frequency characteristic of wind farm harmonic impedance is gained by using the output-error model parameter estimation. The simulation result and outdoor test result illustrate the effectiveness of the proposed method. The proposed method takes a new direction with model identification and system analysis of wind farm harmonic impedance.

1. Introduction

As the scale of access to power systems in wind farms continues to expand, the degree of power electronics in power systems is also increasing, and the impact of wind power access on power system stability is becoming more and more obvious [1-4]. When the wind farm is connected to the power system, not only the fundamental current is injected into the grid, but also a large amount of harmonics are injected. To study the influence of wind farms connected to the power grid on the power system, it is necessary to consider the harmonic impedance model of the wind farm. In addition, the harmonic impedance of the wind farm is also important for the harmonic analysis and equivalent of the power system.

At present, there have been a lot of research results on harmonic impedance and wind power grid-connected resonance. Reference [5] considers the harmonic impedance model of wind turbine, line and reactive power generator, and provides a complete calculation method for harmonic impedance calculation of wind farm. This method is suitable for harmonic impedance of wind farm under the condition of known model parameters. The literature [6] calculated the harmonic level of the wind farm based on the mixed impedance method, but the harmonic impedance of the wind farm is
calculated based on the model and parameters of the wind turbine electrical equipment, and the nonlinear characteristics of the transformer model are not considered. Literature [7] studied the mechanism of wind-electric grid-connected harmonic resonance. The article only analyzes the theoretical model of single-machine example, and does not verify the field measured data. In [8], the open-loop resonant mode is used to study the wind farm resonance problem. This paper only discusses the situation of single-machine resonance, and further verification is needed for large-scale wind power. In [9], the resonance method is used to study the grid-connected resonance analysis of wind farm output power. The method only carries out theoretical analysis and simulation verification, and does not give the verification of measured data.

Firstly, a two-node electrical model is constructed. Considering the conversion relationship between phase variables and line variables, a wind power harmonic impedance model including bus voltage is established, and then the wind farm grid voltage is used as the output, and the wind power is used as the input. The variable, the stochastic subspace is used to obtain the amplitude-frequency characteristics of the harmonic impedance of the wind farm. Finally, the effectiveness of the method is verified by simulation and experiment.

2. Harmonic impedance analysis equivalent model

The wind farm harmonic impedance analysis model is generally represented by a two-node model. The internal resistance of the wind farm represents the harmonic impedance, the wind farm power supply characteristic is equivalent to the harmonic voltage, and the voltage and current equivalent output nodes of the wind farm access point. The voltage and current of the access point are studied as known quantities.

The relationship between the electric quantity of the wind farm and the electrical quantity of the grid connection point is:

$$U_{pcc} = U_s + I_{pcc} Z_s$$  \hspace{1cm} (1)

In the formula (1), $I_{pcc}$ and $U_{pcc}$ are known amounts, and $Z_s$ and $U_s$ are unknown. Equation (1) is applicable to single-phase systems. For three-phase systems, equation (1) can be extended to read as:

$$\begin{bmatrix} U_{pcca} \\ U_{pccb} \\ U_{pccc} \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_{pcca} \\ I_{pcb} \\ I_{pccc} \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix}$$  \hspace{1cm} (2)

Where: $U_{pcca}$ is the PCC point a phase voltage, $U_{pccb}$ is the PCC point b phase voltage, and $U_{pccc}$ is the PCC point c phase voltage. $Z_{aa}$ is the wind farm a phase impedance, $Z_{ab}$ is the a phase and b mutual impedance, $Z_{bc}$ is the c phase and b mutual Impedance, $Z_{ac}$ is the mutual impedance of c-phase and a, $Z_{bb}$ is the self-impedance of b-phase, and $Z_{cc}$ is the self-impedance of c-phase.

When the data acquisition adopts the phase connection mode, it is necessary to consider the wiring relationship between the phase voltage and the line voltage. When writing the equation (2) as the line voltage mode:

$$\begin{bmatrix} U_{pccab} \\ U_{pccbc} \\ U_{pccca} \end{bmatrix} = \begin{bmatrix} Z_{aa} - Z_{ab} & Z_{ab} - Z_{bb} & Z_{ac} - Z_{bc} \\ Z_{ab} - Z_{ac} & Z_{bb} - Z_{bc} & Z_{bc} - Z_{cc} \\ Z_{ac} - Z_{aa} & Z_{bc} - Z_{ab} & Z_{cc} - Z_{ac} \end{bmatrix} \begin{bmatrix} I_{pcca} \\ I_{pcb} \\ I_{pccc} \end{bmatrix} + \begin{bmatrix} U_{sub} \\ U_{svc} \\ U_{sca} \end{bmatrix}$$  \hspace{1cm} (3)

Among them: $U_{pccab}$ is the line voltage between PCC point ab phase, $U_{pccbc}$ is the line voltage between PCC point bc phase, and $U_{pccca}$ is the line voltage between PCC point ca phase.

Since $U_s$ is an unknown quantity, it cannot be directly identified by the stochastic subspace method, and it needs to be converted into an unknown parameter to perform the next identification. Rewrite equation (3) as:
Since the stochastic subspace is for single-output and multi-input models, the model in equation (4) is written as a single-input form, as shown below:

\[
\begin{bmatrix}
U_{pcaab} \\
U_{pcab} \\
U_{pccca}
\end{bmatrix} =
\begin{bmatrix}
Z_{aa} - Z_{ab} & Z_{ab} - Z_{bb} & Z_{ac} - Z_{bc} \\
Z_{ab} - Z_{ac} & Z_{bb} - Z_{bc} & Z_{bc} - Z_{cc} \\
Z_{ac} - Z_{aa} & Z_{bc} - Z_{ab} & Z_{cc} - Z_{ac}
\end{bmatrix}
\begin{bmatrix}
I_{pcaa} \\
I_{pcab} \\
I_{pccca}
\end{bmatrix} +
\begin{bmatrix}
U_{sub} \\
U_{sbc} \\
U_{sca}
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix}
\]  

(4)

Where: 

\[
U_{pcaab} = [Z_{aa}(s) - Z_{ab}(s)]I_{pcaa} + [Z_{ab}(s) - Z_{bb}(s)]I_{pcab} + [Z_{ac}(s) - Z_{bc}(s)]I_{pccca} + U_{sub}(s)*1
\]

(5)

The closer the Afit index is to 1, the less effective the method identification is.

3. Simulation and actual experiment

In order to verify the validity of the method, the error analysis index Afit is defined, and the corresponding expression is:

\[
A_{fit} = \frac{\sum_{i=1}^{n} y_{fit}(i)}{\sum_{i=1}^{n} y(i)} \times 100\%
\]

(6)

Where: 

- \( y_{fit}(i) \) to identify the model output, 
- \( y(i) \) is the simulation model or test waveform output. 
- \( n \) is the number of sampling points.

The closer the Afit indicator is to 1, the better the effect of the method identification in this paper. The closer the Afit index is to 1, the less effective the method identification is.

3.1. Algorithm comparison

To verify the validity and accuracy of the proposed method, the least squares method was chosen as the comparison algorithm. The form of the transfer function corresponding to the test study is as follows:

\[
y = \frac{1 + 0.05s}{s^2 + 1.5s + 0.7s} + e
\]

(7)

Where: 

- \( y \) is the output, 
- \( u \) is the input, and 
- \( e \) is the measurement noise.

Change the noise level in the transfer function separately, compare the identification results under different SNR levels, and calculate the Afit results of the two methods identification model and the model (7) model output according to equation (6). The comparison results are shown in the following figure:

![Figure 1 Identification error of the method in this paper](image-url)
It can be seen from Fig. 1 that the identification results of the proposed algorithm are better than the comparison algorithm under different SNR levels, and the lower the SNR level, that is, the higher the noise, the better the recognition result. In the actual system sampling, there is inevitably some noise in the electrical signal transmitted from the high voltage side to the low voltage side of the transformer. Therefore, the algorithm of this paper is more suitable for the actual system acquisition signal system than the comparison algorithm.

3.2. Simulation analysis
A single-machine infinity system containing a fan is built, and the fan outlet voltage is 690V, which is connected to the 35kV side power grid through a transformer. Collect 35kV three sets of line voltage and phase current. The line voltage is the output variable, the phase current is the input variable, and the power frequency is 60 Hz.

The stochastic subspace method is used to calculate the 35kV bus voltage and three-phase current, and the harmonic impedance of the 35kV side wind farm is calculated. The corresponding amplitude-frequency characteristics are shown in Figure 2. After identification, the transfer function order is 4th order, where the denominator F order is 4th order, and the numerator B order is 3rd order. Afit = 99.33%.

As shown in Figure 2, the wind farm recognizes that the three-phase curve is completely consistent. The parallel resonance point appears at 60 Hz. The impedance amplitude of other frequency bands is much smaller than the harmonic impedance at 60 Hz, indicating that the performance is most obvious in the simulation model. The fundamental electric quantity, the magnitude of other electrical quantities is much smaller than the fundamental amplitude. From another perspective, the output electrical quantity of the simulation model does not truly reflect the impedance characteristics of the non-fundamental frequency band.

3.3. Field Test
The field test scenario is a 110kV busbar of a wind farm. A three-phase short-circuit fault is set on the 110kV busbar, and the fault time is 0.1s; the fault is removed after 0.1s. Record the line voltage and current waveforms during the wind farm fault with a oscillating instrument. The test wiring is wired and wired. After the wind farm collection line is connected to the booster, the voltage is raised from 35kV to 110kV, and then connected to the 220kV grid through the 110kV line. The rated capacity of the fan is 50MW and the main transformer capacity is 60MVA. The power frequency is 50 Hz.

3.3.1 110kV bus line analysis
The stochastic subspace analysis method is used to calculate the 110kV bus voltage and three-phase current, and the harmonic impedance of the 110kV side bus wind farm is calculated. The corresponding
The amplitude-frequency characteristics are shown in Figure 3. After identification, the transfer function order is 6th order, in which the denominator F order is 6th order and the numerator B order is 5th order. \( \text{Afit} = 98.97\% \).

The line voltage impedance data is shown in Figure 3. The single impedance voltage data is shown in Figure 4.

![Figure 3 Harmonic impedance of the 110kV busbar of the wind farm](image)

![Figure 4 Wind farm 110kV bus Zab-Zab harmonic impedance amplitude and real part](image)

It can be seen from Fig. 3 that there is a significant parallel resonance point in the 110kV line voltage harmonic impedance curve, and the parallel resonance point is around 2800Hz. Compared with the 35kV bus harmonic impedance curve of Figure 5, the series impedance point of the 110kV line voltage disappears, indicating that the series resonance point of the system is changed by the boosting function.

According to the literature [12], the stability criterion in the impedance analysis method is as follows:

If there is a resonance point \( f_0 \) in the grid, and the input admittance at \( f_0 \) is positively damped \( \text{Re}(1/Z)>0 \), the grid can remain stable. Even if the system is disturbed, it will not cause harmonic instability. Conversely, when \( \text{Re}(1/Z)<0 \) at the grid side resonance point \( f_0 \), the system will be unstable after the disturbance. In this paper, the real part of the impedance is used instead of the real part of the admittance. The values may be inconsistent, but the sign directions are consistent.

It can be seen from Fig. 4 that \( \text{Re}(1/Z)<0 \) near the parallel resonance point of 2800 Hz, indicating that the resonance point is an unstable resonance point.

The real part minimum value corresponding to the corresponding feature value of the corresponding feature matrix in Fig. 3 is calculated as \(-0.8627\). Consistent with the analysis results of Fig. 4, the Zaa-Zab harmonic impedance exhibits a negative damping characteristic.
3.3.2 35kV busbar result analysis
The stochastic subspace method is used to calculate the 35kV bus voltage and three-phase current, and the harmonic impedance of the 35kV side bus wind farm is calculated. The corresponding amplitude-frequency characteristics are shown in Figure 3. After identification, the transfer function order is 6th order, in which the denominator F order is 6th order and the numerator B order is 5th order. Afit=99.29%.

Figure 5 Harmonic impedance of the 35kV busbar of the wind farm
It can be seen from Fig. 5 that the Zac-Zbc amplitude-frequency curve is close to the Zaa-Zab and Zac-Zbc amplitude-frequency curves, and there is an obvious series resonance point and an obvious parallel resonance point. The first series resonant point frequency is around 380 Hz. The frequency of the first parallel resonance point is about 2800 Hz.

The Zab-Zbb amplitude-frequency curve also has a series resonance point and a parallel resonance point. The frequency of the series resonance point is around 1800 Hz, and the frequency of the parallel resonance point is around 2800 Hz.

Figure 6 Wind farm 35kV bus Zaa-Zab harmonic impedance amplitude and real part
Figure 6 shows the impedance amplitude and real part of the wind farm 35kV bus line Zaa-Zab.

As can be seen from Figure 6, there are two distinct resonance points for Zaa-Zab, 380 Hz and 2800 Hz, respectively. At the resonance point of 380 Hz, the real part of the harmonic impedance is positive, indicating that the resonance point is a stable resonance point. At the resonance point of 2800 Hz, the real part of the harmonic impedance is negative, indicating that the resonance point is an unstable resonance point. If the harmonic interference of the 3800 Hz frequency occurs at the grid connection point of the wind power, harmonic resonance will occur in the system and it cannot be suppressed.
The minimum real part of the corresponding feature value corresponding to the feature matrix in Figure 5 is calculated as -0.8777. Consistent with the analysis result of 6, the Zaa-Zab harmonic impedance exhibits a negative damping characteristic.

3.3.3 Analysis of 690V busbar results of fan outlet

The stochastic subspace method is used to calculate the bus voltage and three-phase current of the 690V fan outlet, and the harmonic impedance of the 690V side bus fan is calculated. The corresponding amplitude-frequency characteristics are shown in Figure 5. After identification, the transfer function order is 5th order, where the denominator F order is 5th order and the numerometric B order is 4th order. Afit = 95.69%.

As shown in Fig. 7, the harmonic impedance of the fan outlet and the harmonic impedance of the 35kV bus of the wind farm show a large difference. The 35kV bus of the wind farm exhibits the characteristics of the parallel resonance point at 2500 to 2800 Hz. The fan 690V outlet exhibits the characteristics of a series resonance point. It shows that the resonance characteristics of the fan change greatly after the fan is connected in parallel and the local boosting and collecting lines.

Extract the first curve in Figure 7, and draw the actual part and the amplitude in the same picture, as shown in Figure 8.

As shown in Fig. 8, the resonance point of the fan 690V bus Zaa-Zab is 2500 Hz, and the real part of the corresponding impedance is also Re(1/Z)<0, indicating that the resonance point is also an unstable resonance point.

The minimum real part of the corresponding feature value corresponding to the feature matrix of Fig. 7 is calculated as -0.6083. Consistent with the analysis result of Fig. 8, the wind farm 690V busbar Zaa-Zab exhibits a negative damping characteristic.

Comparing the 110kV busbar of the wind farm, the 35kV busbar of the wind farm, and the resonance damping value of the 690V busbar, it is found that the resonance problem is more serious...
after the resonance of the fan 690V exits through the convergence line, and the real part of the characteristic value becomes smaller, and the resonance problem is more prominent. After the resonance from the 35kV busbar of the wind farm to the 110kV busbar of the wind farm, the resonance problem is slightly improved, but the numerical change is relatively subtle, indicating that the boosting does not have a significant effect on the damping.

4. Conclusion

In this paper, the stochastic subspace method is applied to the identification process of harmonic impedance parameters of wind farms, which provides a new idea for the study of harmonic impedance of wind farms. The main conclusions of the paper are as follows:

1) The harmonic impedance changes continuously with the amplitude of the frequency. The measured results show that the harmonic impedance has a large harmonic impedance in the low frequency band and gradually decreases after changing to the high frequency band, but exhibits resonance characteristics at individual frequency points. The simulation results show only a certain amplitude-frequency characteristic in the fundamental frequency band, which indicates that the simulation model fails to simulate the harmonic impedance variation law in the field.

2) The wind power resonance impedance has a significant parallel resonance point at 2800 Hz, and the resonance point damping tends to be weakened first from the fan outlet to the 110 kV bus.

3) Wind power harmonic impedance changes significantly from the low voltage 690V to 110kV busbar outlet, indicating that the wind farm convergence line and transformer access significantly change the harmonic impedance of wind power, and also indirectly indicate the strength of the wind farm connected to the grid. It has a significant impact on the frequency point of the harmonic resonance of the wind farm.

The issues that the article needs to further address are:

Through the amplitude-frequency characteristics of wind power harmonic impedance identified by this method, the relationship between the amplitude-frequency characteristics and the control parameters and electrical parameters of the wind farm needs to be further determined, and the physical meaning of the harmonic impedance identification parameters is clarified.

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