Assessment Method of Wind Farm Harmonic Emission Value Based on Improved Complex Linear Regression Model

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Abstract. Wind turbine filter and reactive power compensation devices lead to the harmonic impedance of wind farm is not much larger than that of the utility, so the influence by the wind farm harmonic impedance can not be neglected while assessing the harmonic emission value of wind farm. A method based on improved complex linear regression is proposed in this paper for assessing the harmonic emission value of wind farm. The linear regression model is established by using the harmonic current at PCC point as the explanatory variable and the harmonic voltage of the wind farm as the explanatory variable. The utility harmonic impedance is calculated by complex least squares method. For various of the topology of wind farm feeder network, an equivalent method of feeder network is proposed to calculate the wind farm harmonic impedance. Errors are analyzed by using the error marginal effect of the dispersion parameter. Simulation and measured data verify the effectiveness of the proposed method

1 Introduction

LCL type grid-connected inverter of wind turbine will produce harmonics, which lead to power quality and stability problems [1]. The harmonics of the point of common coupling of wind farm is the result of the internal harmonic source of wind farm and the harmonic source of external power network. Therefore, it is necessary to reasonably classify the harmonic pollution responsibility of PCC point, the premise is to reasonably evaluate the harmonic emission level on both sides of PCC point [2].

A large amount of research on harmonic emission level evaluation methods was carried out. The customer and the utility reference impedance method was proposed in [3]. However, the operating conditions of generator of utility and the load of customer are changing. So, it is hard to calculate the reference impedance accurately according to the utility and customer parameters. Therefore, the non-invasive harmonic emission level assessment method based on the measurement data was proposed, including fluctuation method [4], linear regression method [5], independent random vector method [6], maximum likelihood estimation method [7] and independent component analysis method [8]. The complex linear least square method proposed in [9] is the real solution in the complex domain calculation of least squares regression model, which maintains the strict linear relationship of the regression model and improves the weakness of least squares solution of regression model in the real domain. However, the accuracy of regression results are affected by the collinearity between the PCC harmonic

current and utility harmonics. All the methods above assume that the customer harmonic impedance is much larger than the utility harmonic impedance, so that the customer harmonic impedance is neglected when calculating the harmonic emission level of customer. For typical industrial nonlinear customers (Industrial rectifier loads, arc furnaces, etc.), the above hypothesis holds. However, the wind turbine inverter is equipped with LCL-filter, and the collector point is equipped with reactive power compensation devices, which may cause the harmonic impedance of the wind farm is not much larger than that of the utility, so the influence by the wind farm harmonic impedance can not be neglected.

The harmonic impedance of the wind farm is mainly determined by the wind turbine LCL-filter, transformer, feeder line and reactive compensation capacitor, all of which have definite harmonic impedance model. The wind turbine of same type and capacity is equipped with LCL filters whose parameters are basically consistent. Only the length of line between the wind turbine and collecting point is dispersive, so the structure of the feeder network can be simplified and the harmonic impedance of the wind farm side can be calculated.

In this paper, an improved linear regression model is proposed by using the PCC point harmonic current as the explanatory variable and the harmonic voltage of the wind farm as the explanatory variable. The utility harmonic impedance is calculated by using the complex least square method. Aiming at the variability of topology structure of wind farm feeder network, an equivalent method of collector network is proposed to calculate the wind farm harmonic impedance. The error

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margin effect of the dispersion parameter is used to analyze the error. Simulation and field data verify the effectiveness of the proposed method.

2 Theory of improved complex linear regression model

In this paper, Norton equivalent circuit is commonly used to perform harmonic analysis as shown in Fig.1, where I_U and Z_U are the utility-side equivalent harmonic current and impedance, I_C and Z_C are the wind farm-side equivalent harmonic current and impedance, and U_{PCC} and I_{PCC} are the harmonic voltage and current measured at the PCC.

Figure 1 Norton equivalent circuit of utility and wind farm

Referring to Fig.1, the I_{PCC} can be expressed as

$$I_{PCC} = \frac{Z_C}{Z_U + Z_C} I_C - \frac{Z_U}{Z_U + Z_C} I_U \quad (1)$$

According to Thevenin and Norton transformation, I_{PCC} can be expressed as (2), where V_C and V_U are the equivalent utility-side and wind farm-side harmonic voltage.

$$I_{PCC} = \frac{V_C}{Z_U + Z_C} - \frac{V_U}{Z_U + Z_C} \quad (2)$$

According to Kirchhoff's current law, the wind farm-side equivalent voltage V_C can be calculated as

$$V_C = U_{PCC} + Z_C I_{PCC} \quad (3)$$

The wind farm-side equivalent harmonic impedance can be calculated by parameters of wind farm.

Due to the error of the measured data, the following linear relationship exists between I_{PCC} and V_C can be expressed as (4), where ε is the measurement error.

$$I_{PCC} = \frac{1}{Z_U + Z_C} V_C + \frac{-V_U}{Z_U + Z_C} + \varepsilon \quad (4)$$

A linear regression equation between I_{PCC} and V_C can be established based on (4) as

$$I_{PCC} = \beta_1 V_C + \beta_0 + \varepsilon \quad (5)$$

where β_1 and β_0 are partial regression coefficient.

$\beta_1 = 1 / (Z_U + Z_C)$, $\beta_0 = -V_U / (Z_U + Z_C)$.

During a measurement period, a n group data of PCC point harmonic currents and wind farm side harmonic voltages can be expressed as

$$\begin{cases} I_{PCC}(1) = \beta_1 V_C(1) + \beta_0 + \varepsilon_1 \\ I_{PCC}(2) = \beta_1 V_C(2) + \beta_0 + \varepsilon_2 \\ \dots \\ I_{PCC}(n) = \beta_1 V_C(n) + \beta_0 + \varepsilon_n \end{cases} \quad (6)$$

(6) can be represented as a matrix equation

$$y = Ax + \varepsilon \quad (7)$$

Where $y = [I_{PCC}(1) \ I_{PCC}(2) \ \dots \ I_{PCC}(n)]^T$,

$$A = \begin{bmatrix} 1 & V_C(1) \\ 1 & V_C(2) \\ \vdots & \vdots \\ 1 & V_C(n) \end{bmatrix}, x = \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix}, \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}.$$

In order to minimize the sum of squares of ε , the complex least squares method in [9] is used by

$$x = (\bar{A}^T A)^{-1} \bar{A}^T y \quad (8)$$

where " $\bar{\cdot}$ " stands for conjugate vector.

Compared with the method in [9], there is no correlation between the harmonic current of the wind farm-side and the utility-side harmonic voltage. For the regression results of the equation (7) are not interfered with by the collinearity factor, the regression result is more accurate.

Based on the regression result of β_1 , the utility harmonic impedance can be calculated by

$$Z_U = \frac{1}{\beta_1} - Z_C \quad (9)$$

By the equivalent circuit, the harmonic voltage of PCC point can be expressed as

$$U_{PCC} = \frac{Z_C Z_U}{Z_U + Z_C} I_C + \frac{Z_C Z_U}{Z_U + Z_C} I_U \quad (10)$$

According to the principle of superposition, the harmonic voltage emission value of the wind farm side is

$$U_{PCC-C} = \frac{Z_U Z_C}{Z_U + Z_C} \left(\frac{U_{PCC}}{Z_C} + I_{PCC} \right) \quad (11)$$

And the harmonic voltage emission value of the utility side is

$$\dot{U}_{PCC-S} = \dot{U}_{PCC} - \dot{U}_{PCC-C} \quad (12)$$

3 Calculation of the wind farm side harmonic impedance

2.1 Harmonic model of wind farm

Taking an actual wind farm as an example, the wind farm consists of two parts, one part is the feeder network, which is composed of the wind turbine, transformer and feeder line, the other part is the reactive power compensation device, as shown in Fig.2

Figure 2 Topology of wind farm power station

2.2 Harmonic Impedance Model of PMSG

The permanent magnet synchronous generator (PMSG) consists of wind turbine, permanent magnet synchronous generator, generator side converter, grid side converter and LCL filter. Since the generator side converter and the grid side converter are separated by DC capacitor, the harmonic characteristics of wind turbine are determined only by the harmonic characteristics of the LCL inverter on the grid side.

The harmonic voltage of grid side inverter consists of two parts, one part U_{inv} , is generated by the control system of inverter the other part U_{pwm} , is generated by the dead time and modulation process of inverter. Using the inverter harmonic voltage source and LCL filter to represent the wind turbine harmonic impedance model [10] as shown in Fig.4.

Figure 4 Harmonic model of PMSG-based wind turbine

Where, L_{inv} and L_g are the inverter side and grid side inductance, C_f is the filter capacitor, R_h is the damping resistance.

The harmonic impedance of wind turbine can be obtained by the LCL filter parameter as follows:

$$Z_w(w) = jwL_g + \frac{-w^2 R_h C_f L_{inv} + jwL_{inv}}{-w^2 L_{inv} C_f + jwR_h C_f + 1} \quad (12)$$

Where, w stands for the frequency.

2.3 Harmonic Impedance Model of SVG

The SVG outputs the reactive current through the inverter, in order to suppress the harmonics produced by SVG inverters, L filters are usually connected between the grid and the inverter. In practical engineering, the SVG connection transformer is commonly used as the filter inductance. Accordingly, the harmonic impedance model of SVG is a series harmonic model consisting of the equivalent harmonic voltage source of the inverter and the short-circuit impedance of the transformer connected with the SVG. It can be defined as follows:

$$Z_{SVG}(w) = jwL_T + R_T \quad (13)$$

Where L_T and R_T are the equivalent inductance and resistance of transformer.

2.4 Harmonic Impedance of wind farm side

The impedance of the feeder network can be accurately calculated according to the parameters of the LCL filter, the line impedance and the detailed topology of the feeder network. The harmonic impedance of reactive power compensation device can be calculated, according to the detail parameters. When the measurement point is located on the collector point, the current measured is the total current of the feeder network and the reactive compensation device, the harmonic impedance of the wind farm-side is the parallel

total impedance of the feeder network and reactive power compensation devices.

4 Approximate calculation of the wind farm-side harmonic impedance

In the actual project, it is difficult to obtain the detailed topology of the feeder network, which needs to approximate the harmonic impedance of the feeder network.

4.1 Aggregation equivalence method of feeder network

The topology of the feeder network is changeable, but the parameters of the LCL filter are consistent, only the length of line between the wind turbine and collecting point is dispersive. The equivalent circuit of a single feeder is shown in Fig 5.

Figure 5 Equivalent circuit diagram of single feeder

Where n is the number of the wind turbines, Z_w is the impedance of a single wind turbine, U_h is the harmonic voltage from a single wind turbine. Z_n ($n = 1, 2, 3 \dots n$) is the impedance of the feeder line between adjacent wind turbines, whose sum is the impedance of the feeder line Z_L . Z_f is the impedance of a single feeder.

The impedance of the feeder line is mixed by the wind turbine impedance and the line impedance. Considering that Z_w is much larger than Z_L , the impedance of single feeder can be simplified as follows:

$$Z_f = (Z_w + Z_{eq}) / n \quad (14)$$

Where, Z_{eq} is the equivalent line impedance of a single feeder, it can be obtained by

$$Z_{eq} \approx \sum_{i=1}^n iZ_i = nZ_L - \sum_{i=1}^n (n-i)Z_i \quad (15)$$

By (15), when $Z_i = 0$ ($i = 1, 2 \dots n-1$), $Z_n = Z_L$, that is, the wind turbines are arranged at the end of the feeder, Z_{eq} obtains the maximum value as nZ_L . when $Z_i = 0$ ($i = 2, 3 \dots n$), $Z_1 = Z_L$, that is, only one wind turbine is arranged at the end of the feeder, and the other wind turbines are arranged at the head of the feeder, Z_{eq} obtains the minimum value as Z_L . The boundary value of Z_{eq} can be expressed as follows:

$$Z_L \leq Z_{eq} \leq nZ_L \quad (16)$$

In order to minimize the impedance error of the feeder network between the approximation and the true values, the impedance approximation of feeder network Z_{FJS} is defined as the mean value of the maximum and minimum by

$$Z_{FJS} = \left(Z_w + \frac{Z_{Lmin} + n_{max} Z_{Lmax}}{2} \right) / N \quad (21)$$

Where, Z_{Lmin} and Z_{Lmax} are the impedance of the shortest and the longest feeder lines. n_{max} is the maximum number of wind turbines connected to a single feeder.

4.2 Approximate Error of Harmonic Impedance in feeder Network

Take an actual wind farm as an example, there is 5 feeders in the wind farm, each of which is equipped with 10 wind turbines. The length of feeder line is 4.7km, 8.0km, 11.2km, 13.5km, 15.5km, respectively. Parameters of wind turbine and LCL filters is shown in Table1. The short circuit inductance of step-up transformer is used as the grid side inductance of LCL filters, whose value is 0.041mH.

Table 1. Parameters of wind turbine and filter

Parameters	Value
Rated Power P/MW	2.0
Rated Voltage U_g /kV	0.69
Rated Capacity S_T /MVA	2.2
Rated Voltage of transformer U_T /kV	0.69/37
Short-circuit impedance of transformer %	6%
Inverter side inductance L_{inv} /mH	0.18
Grid side inductance L_g /mH	0.04
Filter capacitor C_f /uF	700
Filter resistor R_f /Ω	0.1

Consider the extreme conditions that may exist in the topology of feeder network: the wind turbines adopts an end or head arrangement, and the length of the feeder l is the shortest or the longest. The error of primary harmonic approximate impedance of the feeder network is shown in table2.

Table 2. Errors of harmonic impedance approximation of feeder network

Errors of Harmonic Impedance Approximation of Feeder Network (%)					
Harmonic order		5th	7th	11th	13th
End arrangement	Longest line	-0.5	-0.35	0.5	1.1
	Shortest line	10.0	6.2	-6.9	-16.1
Head arrangement	Longest line	-5.1	-3.2	3.8	10.2
	Shortest line	-4.1	-2.6	3.1	7.8
Accurate value		-1.1	-0.7	0.7	2.0

Taking the 5th harmonic as an example, in order to show the relationship between the feeder network impedance and the number of wind turbines, the harmonic admittance of the feeder network is shown in Fig.6.

Figure 6 Amplitude of feeder network of 5th harmonic admittance

Where, the red curve represents the approximate value of admittance, and the black curve represents the

exact value. The green and blue curves represent the end and head arrangement of wind turbines, respectively. The corresponding solid lines and dashed lines represent the conditions of shortest and longest lines.

Obviously, with the increase of the number of the wind turbine, the accurate harmonic admittance of the feeder network almost increases linearly, and the maximum error of the approximate harmonic impedance value is only -16.1%.

4.3 Approximation of wind farm-side harmonic impedance

Other parameters of the wind farm are shown in table3.

Table 3. Parameters of wind farm

Parameters	Parameter Description
Short-circuit	35kV:766MVA
Capacity	220kV:11090MVA
Step-up Transformer	Rated Voltage 230±8×1.25%/37kV, Rated Capacity 100MVA, Connection Sets: Yyn0, Short-circuit Impedance of Transformer: 6%
Fixed Capacitor	Rated Capacity 12Mvar, Capacitor Series Reactance Rate: 6%, Quality Factor: 100.
SVG	Rated Capacity 9Mvar, Rated Voltage: 10kV
SVG Transformer	Rated Voltage 37±2×2.5%/10kV, Rated Capacity 10MVA, Connection Sets: Yyn0, Short-circuit Impedance of Transformer: 10%

When the measurement point is located in the 35kV bus (collecting point), the minimum, maximum, accurate and approximate values of the primary harmonic impedances of wind farms side are shown in table 4

Table 4. Harmonic impedance boundary value of wind farm

Harmonic impedance boundary value of wind farm(Ω)				
Harmonic order	Minimum value	maximum value	Accurate value	Approximate value
5th	7.8∠88°	8.1∠88°	7.9∠88°	7.9∠88°
7th	20.1∠86°	20.8∠86°	20.3∠86°	20.4∠86°
11th	64.4∠17°	79.6∠19°	74.9∠18°	74.2∠18°
13th	26.3∠-14°	40.9∠-30°	35.7∠-25°	34.9∠-25°

From table 4, the maximum amplitude error of the 5th, 7th, 11th, 13th harmonic impedance approximation is 2.5%, 1.9%, 13.2% and 24.6%, respectively.

The utility harmonic impedances can be roughly calculated by the short-circuit capacity of measuring point, which are 9, 13, 20, 23Ω for 5th, 7th, 11th, 13th harmonic respectively. So, the amplitude of wind farm harmonic impedance is not much larger than the utility side.

5 Harmonic impedance boundary value of wind farm with parameter error

There is an error between the actual parameters and the rated parameters of the component, resulting in a change in the impedance of the wind turbine within a certain range. There is a error in the capacity of filter inductance and filter capacitor, which is generally

believed to 5% as maximum [11]. And there is a error in short-circuit impedance of transformer, which is generally believed to 10% as maximum.

The inductance of the filter, the capacity of the capacitor, and the short-circuit impedance of transformer may increase or decrease at the same time. Based on analysis and comparison, the 5th, 7th harmonic impedance increase and the 11th, 13th harmonic impedance decrease, when L_{inv} , C_f and L_g increase, vice versa.

When the filter parameter error is the maximum value, the boundary value of single wind turbine is shown in Fig7.

Figure 7 Amplitude of wind turbine harmonic impedance

In order to avoid resonance between filter and power grid, the tuning point is designed on the frequency of non integer harmonic according to the principle of partial resonance.

As shown in Fig8, the actual resonance point of the filter is designed between 430Hz-471Hz with parameter errors of LCL filter, witch is from the primary integer harmonics.

Therefore, the error of filter parameters will not lead to changes in impedance properties of wind turbine. So, there is no interference between the inductive and capacitive impedances of wind turbines.

The boundary value of the impedance of the feeder network can be obtained by the boundary value of the impedance of each wind turbine.

Considering the parameter error of component and the approximation error of the feeder network, the boundary error of the harmonic impedance of the feeder network and the corresponding boundary value of harmonic impedance of the wind farm can be calculated as shown in table 5 and table 6, respectively.

Table 5. Harmonic impedance boundary error of feeder network

Harmonic impedance boundary error of feeder network(%)				
Harmonic order	5th	7th	11th	13th
Minimum value	-13.6	-17.9	-28	-32
maximum value	19.2	25.1	34.2	33.9

Table 6. Harmonic impedance boundary value of wind farm with parameter error

Harmonic impedance boundary value of wind farm(Ω)				
Harmonic order	Minimum value	maximum value	Accurate value	Approximate value
5th	7.6∠88°	8.3∠88°	7.9∠88°	7.9∠88°
7th	19.0∠86°	21.8∠85°	20.3∠86°	20.4∠86°
11th	52.7∠3°	78.9∠37°	74.9∠18°	74.2∠18°
13th	20.2∠-10°	52.9∠-24°	35.7∠-25°	34.9∠-25°

From table 6, the maximum error of approximate value of wind farm impedance is 5%, 7%, 30% and 52% for 5th, 7th, 11th, 13th harmonic respectively.

6 Simulation and field data analysis

6.1. Simulation analysis

A computer simulation study was performed by Matlab7.0, which was based on the Norton equivalent circuit shown in Fig.1, including 1440 sample points at PCC.

The parameter was set as follows (the percentage of disturbance indicates the maximum of uniform disturbance comparing to initial value):

1) The amplitude of I_C is 150A, and that of I_U is 0.5 times smaller. Phase angles of I_C and I_U are respectively and 30° and 50°. 10% sine fluctuation and 10% random disturbance are added to the phase angles of I_C . 5% sine fluctuation and 20% random disturbance are added to the amplitude of I_C . 10% sine fluctuation and 10% random disturbance are added to the phase angles of I_U . 5% sine fluctuation and 10% random disturbance are added to the amplitude of I_U

2) The amplitude of Z_U is set as the rough values of utility harmonic impedance in the foregoing paragraph. Phase angles of Z_U is 70°. 10% sine fluctuation and 20% sine fluctuation are added to amplitude and angles of Z_U respectively. Z_C is set as the values in tableV and tableVI.

With 100 sample points for each subinterval, sliding analysis is performed. The results errors of method in [9] (method a) and method proposed in this paper (method b) was compared. With the approximate error of feeder network is taken into account, the errors of utility impedance and harmonic voltage emission value of wind farm are shown in table 7 and table 8.

Table 7. Errors of utility harmonic impedance amplitude

Root mean square value of the relative error (%)						
Z_C	Minimum value		maximum value		Accurate value	
Method	a	b	a	b	a	b
5th	10.2	5.1	10.5	5.3	9.0	4.1
7th	8.9	5.4	9.2	5.3	8.7	3.5
11th	7.8	4.6	5.6	3.6	7.2	3.2
13th	8.6	4.4	9.0	4.5	7.5	3.8

Table 8. Errors of harmonic voltage emission value of wind farm

Root mean square value of the relative error (%)						
Z_C	Minimum value		maximum value		Accurate value	
Method	a	b	a	b	a	b
5th	52.2	3.1	49.8	3.5	50.9	3.4
7th	30.8	3.2	28.1	2.8	27.8	3.0
11th	5.6	3.6	5.2	3.9	4.8	3.2
13th	28.2	10.8	29.1	5.4	30.4	4.6

With the approximate error of feeder network and the parameter errors of LCL filters are taken into account, the errors of utility impedance and harmonic voltage emission value of wind farm are shown in table 9 and table 10.

Table 9. Errors of utility harmonic impedance amplitude

Root mean square value of the relative error (%)						
Z_C	Minimum value		maximum value		Accurate value	
Method	a	b	a	b	a	b
5th	8.9	4.8	11.3	5.9	9.0	4.1
7th	8.0	5.3	8.9	6.1	8.7	3.5
11th	7.5	4.3	10.3	6.0	7.2	3.2
13th	8.0	5.0	6.8	4.3	7.5	3.8

Table 10. Errors of harmonic voltage emission value of wind farm

Root mean square value of the relative error (%)					
Z_c	Minimum value		maximum value		Accurate value
Method	a	b	a	b	a b
5th	52.1	3.6	48.2	3.5	50.5 3.0
7th	30.6	2.2	25.0	5.7	29.1 6.7
11th	5.3	3.2	7.2	5.8	4.6 3.3
13th	28.2	17.4	26.6	4.7	29.8 4.3

It can be easily learned from table VII-X that method b has the smaller errors than method a, no matter the harmonic impedance of wind farm is the accurate value or the boundary value.

The actual impedance of the wind farm is within the range of the maximum and minimum boundary values. So, the method proposed in this paper has smaller errors of the utility harmonic impedance and the harmonic voltage emission value.

6.2. Field data analysis

To further verify effectiveness of the proposed method, field data are used to perform calculation. The measured data are drawn from the collecting point of the actual wind farm described above. The harmonic current of the feeder network and the harmonic voltage of PCC point is sampled. Harmonic data are acquired by using FFT algorithm to analyze sample data per minute. The 5th harmonic current and voltage is shown in Fig8.

Method proposed in this paper and method in [9] are used to calculate the utility impedance and the harmonic voltage emission value of wind farm as shown in Fig9.

Figure 8 5th harmonic voltage and current of PCC

Figure 9 Estimates of the 5th utility harmonic impedance

The utility and wind farm side harmonic voltage emission value (95% probability value) obtained by the method in [9] are respectively 231V and 174V. However the utility and wind farm side harmonic voltage emission value (95% probability value) obtained by the method proposed by this paper are respectively 308V and 79V, which is quite different. Based on the analysis result of the simulations, the method proposed is more accurate.

6 Conclusion

In this paper, an assessment method of wind farm harmonic emission value based on improved complex linear regression model is proposed. Simulation and field data analysis verify the effectiveness and superiority of the proposed method. How to calculate the impedance of wind farm easily in engineering survey, through the component parameters acquired by the wind farm is the further research direction

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