ASSESSMENT OF HARMONIC EMISSION VALUE OF DISTRIBUTED GENERATION SYSTEM IN MICROGRID BASED ON IMPROVED COMPLEX LINEAR REGRESSION

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ABSTRACT

LCL filters of distributed generation (DG) and reactive power compensation devices may cause the harmonic impedance of distributed generation system (DGS) to be not much larger than that of the utility, so the influence by the harmonic impedance of DGS can not be ignored while assessing the harmonic emission value of DGS A method based on improved complex linear regression is proposed in this paper for assessing the harmonic emission value of DGS. The linear regression model is established by using the harmonic current at PCC point as the explanatory variable and the harmonic voltage of the DGS as the explanatory variable. The utility harmonic impedance is calculated by complex least squares method. For various of the topology of DGS feeder network, an equivalent method of feeder network is proposed to calculate the harmonic impedance of DGS. Simulation and measured data verify the effectiveness of the proposed method

INTRODUCTION

LCL type grid-connected inverter of DG will produce harmonics, witch lead to power quality and stability problems. The harmonics of the PCC (point of common coupling) is the result of the internal harmonic source of DGS and the harmonic source of external power network. Therefore, it is necessary to reasonably classify the harmonic pollution responsibility of PCC, the premise is reasonably evaluating the harmonic emission level.

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 [1]. 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, linear regression method, independent random vector method[2], maximum likelihood estimation method and independent component analysis method. The complex linear least square method proposed in 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 DG is often equipped with LCL-filter, and the collector point is equipped with reactive power compensation devices, which may cause the harmonic impedance of DGS is not much larger than that of the utility, so the influence by the harmonic impedance of DGS can not be neglected.

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 DGS 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 DGS feeder network, an equivalent method of feeder network is proposed to calculate the harmonic impedance of DGS. The error margin effect of the dispersion parameter is used to analyze the error. Simulation and field data verify the effectiveness of the proposed method.

THEORY OF IMPROVED COMPLEX LINEAR REGRESSION MODEL

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 DGS-side equivalent harmonic current and impedance, and U_{PCC} and I_{PCC} are the harmonic voltage and current measured at the PCC.

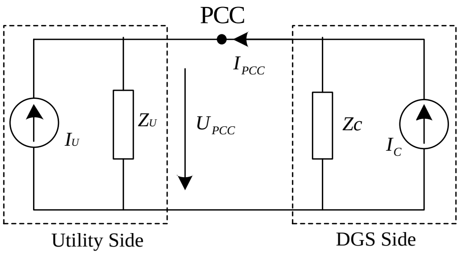

Figure 1 Norton equivalent circuit of utility and DGS

Referring to Fig.1 and according to Thevenin and Norton transformation, I_{PCC} can be expressed as

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

where V_C and V_U are the equivalent utility side and DGS-side harmonic voltage.
According to Kirchhoff's current law, the DGS-side equivalent voltage V_C can be calculated as

$$V_C = U_{PCC} + Z_C I_{PCC} \quad (2)$$

The DGS-side equivalent harmonic impedance can be calculated by parameters of DGS.
Due to the error of the measured data, the following linear relationship exists between I_{PCC} and V_C can be expressed as (3), where ε is the measurement error.

$$I_{PCC} = \frac{1}{Z_U + Z_C} V_C + \frac{-V_U}{Z_U + Z_C} + \varepsilon \quad (3)$$

A linear regression equation between I_{PCC} and V_C can be established based on (3) as

$$I_{PCC} = \beta_1 V_C + \beta_0 + \varepsilon \quad (4)$$

where β_1 and β_0 are 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 DGS-side harmonic voltages can be expressed as a matrix equation

$$y = Ax + \varepsilon \quad (5)$$

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

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

In order to minimize the sum of squares of ε, the complex least squares method in [3] is used by

$$x = (\bar{A}^T A)^{-1} \bar{A}^T y \quad (6)$$

where "¯" stands for conjugate vector.
Compared with the method in [3], there is no correlation between the harmonic current of the DGS-side and the utility-side harmonic voltage. For the regression results of the equation (4) are not interfered with by the collinearity factor, the regression result is more accurate.
The utility harmonic impedance can be calculated by

$$Z_U = \frac{1}{\beta_1} - Z_C \quad (7)$$

According to the principle of superposition, the harmonic voltage emission value of the DGS-side is

$$U_{PCC-C} = \frac{Z_U Z_C}{Z_U + Z_C} \left(\frac{U_{PCC}}{Z_C} + I_{PCC} \right) \quad (8)$$

And the harmonic voltage emission value of the utility side is

$$\dot{U}_{PCC-S} = \dot{U}_{PCC} - \dot{U}_{PCC-C} \quad (9)$$

CALCULATION OF THE DGS SIDE HARMONIC IMPEDANCE

Harmonic model of DGS

By taking a DGS in a microgrid as an example, the DGS often consists of two parts, one part is the feeder network, which is composed of DGs and feeder line, the other part is the reactive power compensation device, as shown in Fig.2

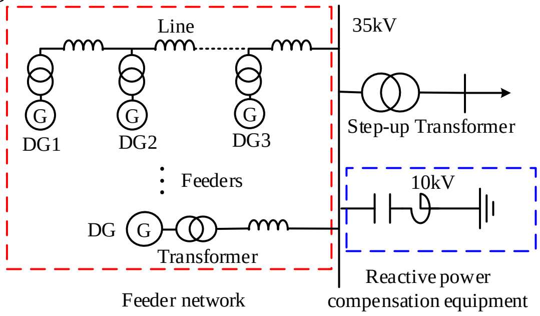

Figure 2 Topology of DGS

Harmonic Impedance Model of DG

Most of DG use inverters to convert power and connect to microgrid. The harmonic characteristics of DG are determined by the LCL-based grid-connected inverters [4]. The inverter harmonic voltage source and LCL filter are used to represent the harmonic model of inverter based DG as shown in Fig.3.

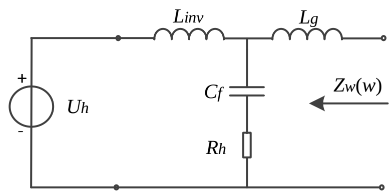

Figure 3 Harmonic model of inverter based DG

Where, L_{inv} and L_g are the inverter side and grid side inductance, C_f is the filter capacitor, R_h is the resistance.
The harmonic impedance of DG can be obtained by the LCL filter parameter as follows:

$$Z_W(w) = jwL_g + \frac{-w^2 R_h C_f L_{inv} + jwL_{inv}}{-w^2 L_{inv} C_f + jwR_h C_f + 1} \quad (10)$$

Where, w stands for the harmonic frequency.

APPROXIMATE CALCULATION OF DGS SIDE HARMONIC IMPEDANCE

In the actual project, it is hard to obtain the detailed topology of the feeder network, which needs to calculate the harmonic impedance of DGS feeder network approximately.

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 DGS and collecting point is dispersive. The equivalent circuit of a single feeder is shown in Fig 4.

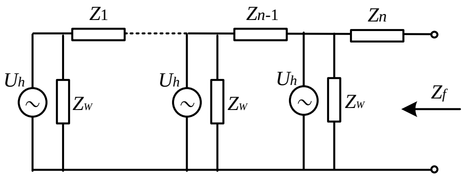

Figure 4 Equivalent circuit diagram of single feeder

Where n is the number of the DG, Z_W is the impedance of a DG, U_h is the harmonic voltage of a single DG. Z_n (n = 1, 2, 3 ... n) is the impedance of the feeder line between adjacent DG, 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 impedance of DG and impedance of line. Considering that Z_W is much larger than Z_L, the impedance of single feeder can be simplified as follows:

$$Z_f = \left(Z_W + Z_{eq}\right)/n \tag{11}$$

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

$$Z_{eq} \approx \sum_{i=1}^{n} iZ_i = nZ_L - \sum_{i=1}^{n}\left(n-i\right)Z_i \tag{12}$$

By (12), when $Z_i = 0$ (i = 1,2 ... n-1), $Z_n = Z_L$, that is, DGs are arranged at the end of the feeder, Z_{eq} obtains the maximum value as nZ_L. when $Z_i = 0$ (i = 2,3 ... n), $Z_1 = Z_L$, that is, only one DG is arranged at the end of the feeder, and the other DGs 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:

$$Z_L \le Z_{eq} \le nZ_L \tag{13}$$

The impedance approximation of feeder network Z_{FJS} is defined as the mean value of the maximum and minimum.

$$Z_{FJS} = \left(Z_W + \frac{Z_{L\min} + n_{\max} Z_{L\max}}{2}\right)/N \tag{14}$$

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

Approximate Error of Harmonic Impedance of DGS in feeder Network

Take a DGS consist of PMSG based wind turbine as an example, there is 5 feeders in the DGS, each of which is equipped with 10 DGs. The length of feeder line is 4.7km, 8.0km, 11.2km, 13.5km, 15.5km, respectively. Parameters of DG and LCL filters is shown in Table1.

Table 1. Parameters of DG and filter

Parameters	Value
Rated Power P/MW	2.0
Rated Voltage U_g/kV	0.69
Rated Voltage of transformer U_T/kV	0.69/37
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_h/Ω	0.1

Other parameters of DGS are shown in table2.

Table 2. Parameters of DGS

Parameters	Parameter Description
Short-circuit	35kV:766MVA
Fixed Capacitor	Rated Capacity 12Mvar, Capacitor Series Reactance Rate: 6%, Quality Factor: 100.

Consider the extreme conditions that may exist in the topology of feeder network: the DGs adopts an end or head arrangement, and the length of the feeder is the shortest or the longest. 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 DGS-side are shown in table 3

Table 3. Harmonic impedance boundary value of DGS

Harmonic impedance boundary value of DGS(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 3, 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 harmonic impedance of DGS is not much larger than the utility side.

BOUNDARY VALUE OF DGS HARMONIC IMPEDANCE

There is an error between the actual parameters and the rated parameters of the component, resulting in a change in the impedance of the DGS within a certain range. There are errors in the capacity of filter inductance and filter capacitor, which is generally believed to 5% as maximum. Based on analysis and comparison, the 5^{th}, 7^{th} harmonic impedance increase and the 11^{th}, 13^{th} harmonic impedance decrease, when L_{inv}, C_f and L_g increase, vice versa. Considering the parameter error of component and the approximation error of the feeder network, the boundary error of the harmonic impedance of DGS can be calculated as shown in table 4.

Table 4. Harmonic impedance boundary value of DGS with parameter error

Harmonic impedance boundary value of DGS(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 4, the maximum error of approximate value of DGS-side harmonic impedance is 5%, 7%, 31% and 51% for 5th, 7th, 11th, 13th harmonic respectively.

SIMULATION AND FIELD DATA ANALYSIS

Simulation analysis

A computer simulation study was performed, which was based on the Norton equivalent circuit, including 1440 sample points at PCC. The parameter was set as follows:
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 30º and 50º. 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 70º. 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 table4.
With 100 sample points for each subinterval, sliding analysis is performed. The errors of utility impedance and harmonic voltage emission value of DGS are shown in table 5 and table 6, where method a stands for method in [3], method b stands for method proposed in this paper.

Table 5. 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 6. Errors of harmonic voltage emission value of DGS

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 5-6 that method b has the smaller errors than method a, no matter the harmonic impedance of DGS is the accurate value or the boundary value. The actual impedance of the DGS is within the range of the maximum and minimum boundary values. So, the method proposed in this paper has smaller errors.

Field data analysis

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 Fig5. Results by method and method b are shown in Fig6.

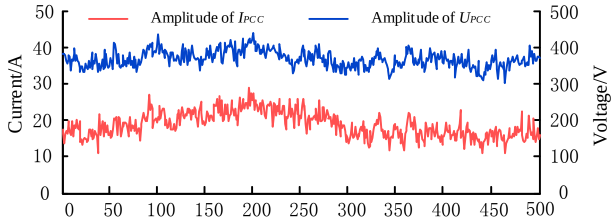

Figure 5 5th harmonic voltage and current of PCC

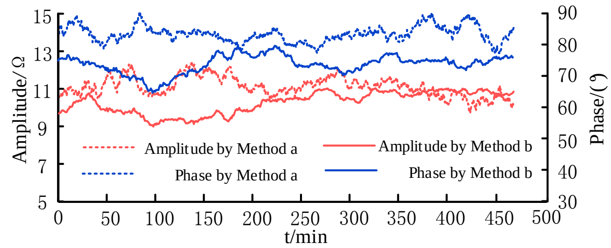

Figure 6 Estimates of the 5th utility harmonic impendance

The utility and wind farm side harmonic voltage emission value (95% probability value) obtained by method a are respectively 231V and 174V, which is far from 308V and 79V obtained by the method proposed. Based on the analysis result of the simulations, the method proposed is more accurate.

CONCLUSION

An assessment method of distributed generation system 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.

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