Research on Harmonic Characteristics Influence for Distribution Network with Renewable Energy

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Abstract. In order to study the influence on harmonic characteristics of distribution network with renewable energy, a simplified model of distribution network is established to analyse theory while considering the influence of cable on the system capacitive current. Establishing an actual distribution network model by Digsilent to research the harmonic characteristics impact when photovoltaic power with PV incorporated the distribution network in a variety of different access , while using constant current source model as harmonic source model which often been used in engineering practices. The simulation results show that: optimizing the access location and dispersion of PV can decrease the waveform distortion levels in distribution network and a certain number of high-order harmonic will magnify by a specific grid structure, deteriorating the distribution network power quality.

1 Introduction

Fossil fuels, mainly including oil, coal and natural gas-based, is gradually coming to exhaustion, and in response to the energy crisis, governments began to put renewable energies, such as wind power and solar power onto the strategic agenda [1]-[3]. The proportion of non-fossil energy sources in total energy will increase to about 20%, according to the <Energy Development Strategy Action Plan (2014-2020)> proposed by Chinese government.

Photovoltaic (referred to as PV) roof and small household wind power, which are both classified as renewable energy, will change the power structure of the distribution network, resulting in complex effects on the network [4]. Most of the renewable energies have to be transformed into industrial frequency current using power electronic devices before grid-connected, causing inevitable harmonics injection [5], which will not only increase extra losses and accelerate the aging of transformers, capacitors, cables and other power equipment, but also brings higher production error to enterprise customers who have significant waveform quality sensitivity, leading to unnecessary losses.

Distributed PV is one of the most potential renewable energy technologies, but which produces significant harmonics, so a study on how renewable energy would influence the harmonic characteristics of distribution network , where the three-phase PV inverters [6] act as study object, has been made in this paper. However, the complexity of distribution network [7], as well as diversity of how and where the PV generation will be connected to the public grid, brings the harmonic analysis of distribution network great challenges. Models of power electronic devices and distribution network have been built in [8], where harmonic characteristics of distribution network integrated with DG are analysed in detail, but only the effects of high-order harmonics under ideal conditions are taken into major consideration. The linear and nonlinear models of DP in ideal distribution network system have been respectively studied in [9], but it distribution network' take the impact of cable earth capacitance in actual distribution network into account.

In the actual generated by PV inverter harmonic component is very complex, harmonic frequency covers from 2th to 25th and even higher. And there are a lot of branch in practical distribution network, capacitive parameters of branch will make some harmonic amplification, different grids will form different amplification characteristics. In addition to that, two or more PV system may be accessed in the same distribution network, making voltage distribution become more complicated. The actual parameters must be selected so that the simulation result will be close to actual situation.

In this paper an actual model of inverter is chosen to simulate the PV systems, and a model of PV harmonic source whose fundamental information came from factory test data has been built. Effects of grid-connection of renewable energy generation on harmonic characteristics in distribution network, was exhaustively studied by changing the factors including how and where the PV is grid-connected, PV capacity, etc. A simulation of actual distribution network has been made using Digsilent Power Factory, indicating that, the level of waveform distortion in distribution network would be lowered by optimizing location and manner of dispersion of PV grid-connection, and some particular grid structures could amplify one or several degrees'

DOI: 10.1051/matecconf/20167010004

harmonics, which causes severe harmonic distortion that the system can't bear damaging the system.

2 Harmonic analysis

PV inverters, which would generate a mass of harmonic currents, must be installed between the solar power plant and public grid, causing voltage distortion on buses. The amount of distortion is related to location of PV grid-connection and PV capacity, and in order to simplify the analysis, a simple distribution network with single radiation feeder has been designed, as shown in Figure 1, where:

M, L	Distance from equivalent bus to PV and from load to equivalent bus, in km
δ_G ,Vg	Voltage angle and amplitude in V at PV connection node
P_G, Q_G	Active power and reactive power exported by PV, in kW and kvar
P_D, Q_D	Active power and reactive power consumed by load, in W and var
φ_G, φ_D	Power factor angle of PV and load
V_D	Voltage amplitude of load node, in kV

And the unit impedance of the transmission line is set to $r + jx$, in Ω/km, while b in S/km for susceptance.

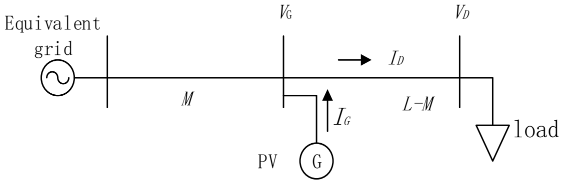

Figure 1. PV connected to distribution network.

3 Influence of PV access on harmonics

Amplitude of fundamental current IG flowing out from PV is:

$$I_G = \left|P_G/\left(V_G COS\varphi_G\right)\right| \tag{1}$$

Similar to Hth-degree harmonic of load current, that of PV injection current is expressed by ratio of its amplitude to that of fundamental current, referred to as I_G^h, then amplitude of Hth harmonic injection current is:

$$I_{Gh} = I_G I_G^h = \left|P_G/\left(V_G COS\varphi_G\right)\right| I_G^h \tag{2}$$

And its angle is:

$$\theta_{Gh} = \theta_G^h + h(\delta_G - \varphi_G) \tag{3}$$

Assuming that θ_G^h, angle of Hth harmonic current of PV, is 0, and the power factor of PV is close to 1, the φ_G has a very small value near 0. And because a line in distribution network is short, with a small value of r/x, resulting in δ_G close to 0, then the θ_{Gh} is 0. Similarly, angle of Hth harmonic injection current of load is also 0. Amplitude of Hth harmonic voltage at terminal node can be represented as:

$$V_{Dh} = \sqrt{\frac{(hx)^2 + r^2}{(2hbrM)^2 + \left(2h^2bxM - \frac{1}{M}\right)^2}} I_{Gh} + \sqrt{\frac{(hx)^2 + r^2}{(2hbrL)^2 + \left(2h^2bxL - \frac{1}{L}\right)^2}} I_{Dh} \tag{4}$$

The system equivalent model after PV grid-connected is shown in Figure 2.

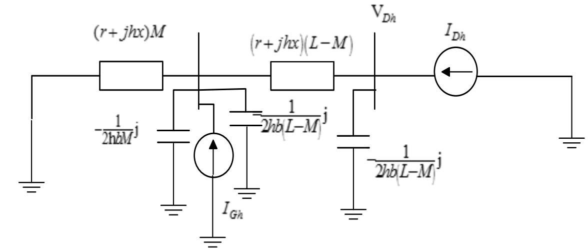

Figure 2. PV connected to distribution network model.

Change of the amplitude of Hth harmonic voltage at terminal node after PV grid-connected:

$$\Delta V_{Dh} = \sqrt{\frac{(hx)^2 + r^2}{(2hbrM)^2 + \left(2h^2bxM - \frac{1}{M}\right)^2}} \left|\frac{P_G}{V_G}\right| I_G^h \tag{5}$$

As it can be found out from Equation (5), after PV grid-connected, voltage distortion at nodes along with lines is related to connected capacity P_G, access location M, and the distortion of harmonic source itself, which depends on manufacturing level of electronic devices. Besides, the higher the degree of distortion of harmonic source itself or the connected capacity raising the increment of harmonic voltage amplitude, the severer the system voltage distortion. For the impact of the access location, it should be discussed in two cases below:

1) Lines behind connection point

Assume Z, a position ahead of the connection point, where Z<M, then amplitude of Hth harmonic voltage at that point could be expressed as:

$$V_{Zh} = \sqrt{\frac{(hx)^2 + r^2}{(2hbrZ)^2 + \left(2h^2bxZ - \frac{1}{Z}\right)^2}} \left(I_{Gh} + I_{Dh}\right) \tag{6}$$

It is called constant power model if PV is generally not involved in voltage regulation, and it's indicated by voltage quality analysis that, a greater access location causes a greater V_G, then a smaller I_{Gh}. Similarly, voltage fall decreases and then terminal voltage goes up with the access location M increasing. The I_{Dh} would decrease with the terminal voltage rising, so that the V_{Zh} in Equation (6) would be reduced, so is the voltage distortion.

2) Lines behind connection point

Assume Z, a position behind the connection point, where Z>G, then amplitude of Hth harmonic voltage at that point can be expressed as:

$$V_{Zh} = \sqrt{\frac{(hx)^2 + r^2}{(2hbrM)^2 + \left(2h^2bxM - \frac{1}{M}\right)^2}} I_{Gh} + \sqrt{\frac{(hx)^2 + r^2}{(2hbrZ)^2 + \left(2h^2bxZ - \frac{1}{Z}\right)^2}} I_{Dh} \quad (7)$$

As indicated in Equation (7), although b value of a cable line is relatively great, but still at a small magnitude. If *h* is small, the greater M, the smaller the overall value of $(2hbrM)^2 + (2h^2bxM - 1/M)^2$; When h has a greater value, and the harmonic current injection I_{Gh} is small, the total voltage distortion would be less affected by corresponding degrees' harmonics voltage increment. Therefore, voltage distortion on the lines behind the connection point goes greater as the connection position M does.

4 Analysis on influence of system response on harmonics

To improve the voltage quality at terminals and power supply reliability, power supply enterprises gradually enhance the reactive compensation devices in 10kV distribution networks in the process of renovation of urban and rural power grids. Inductive reactance of a long branch and capacitive reactance of a compensation capacitor exactly form a series circuit, besides, to facilitate the analysis of the corresponding harmonic characteristics, the resistance is ignored here, as shown in Figure 3.

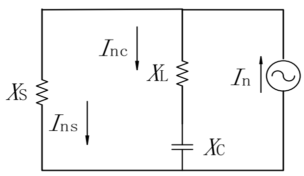

Figure 3. Equivalent network model.

I_n, I_{nc}, I_{ns}	Total Nth-degree harmonic current, and that flows into branch side and system side
X_C, X_L, X_S	Capacitive reactance of compensator, inductive reactance of branch and system

And harmonic impedance of an inductor is proportional to frequency, while that of a capacitor is inversely proportional to frequency. Thus parallel resonance occurs as harmonic degree increases to n_x, and n_x and around n_x degrees' harmonic currents will be amplified by the resonant circulation, corresponding harmonic voltage distortion will be amplified too. In addition, a greater branch capacitance results in a smaller n_x.

5 Simulation and analysis

5.1 Example introduction

The distribution network model used in this paper comes from a chain feeder along the direction of the switching station in 10kV distribution network in a certain city in Guangdong Province, which is a lone line to stretch from the switching station to the load nearby. Its grid structure and specified parameters are shown in Figure 4 and Table 1.

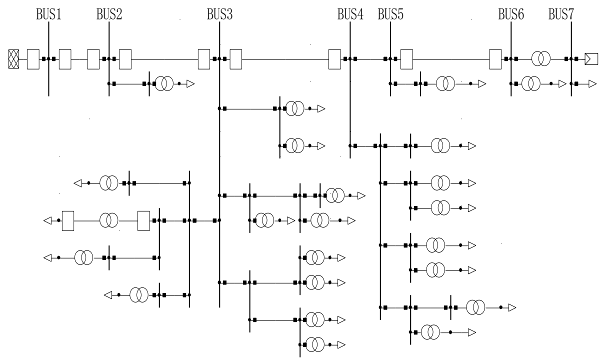

Figure 4. Structure of China feeder.

Bus 1 is the 10kV bus of substation, while other buses are switching stations along line. Loads mainly consist of schools, malls and residential area, whose changes has a certain amount of time characteristics.

Table 1. Equivalent parameters of a feeder.

No.	Line	Line model	Length/ km	Active power/ MW	Reactive power/ Mvar
1	0-1	YJV-300	1.95	0.460	0.044
2	1-2	YJV-300	1.28	1.905	0.342
3	2-3	YJV-3×300	1.80	1.383	0.252
4	3-4	YJLV-240	0.25	0.725	0.104
5	4-5	YJLV-240	0.10	0.440	0.116
6	5-6	YJV-150	0.47	0.219	0.057

5.2 Description of simulated cases

Access location, capacity, methods and different load conditions of distributed photovoltaic power will cause different effects on the distribution network of power quality. Several typical access cases are chosen to make a simulation analysis. Details are shown in Table 2.

Table 2. Simulation cases illustrate.

-	Access location	Load	Power factor	Output
1	Bus7	30%	-0.98	100%
2	Variety	80%	-0.98	100%
3	Dispersed	80%	-0.98	100%

Note: Percentage in the above table is percentage of maximum load capacity.

5.3 Influence of change of access location on harmonics

Figure 5, a diagram of the total voltage distortion rate of each node in case 2, shows that without the harmonic source model, access method and access capacity changing, the closer to the system bus the distributed PV position is, the lower the level of harmonic distortion of the line is as a whole. On the contrary, the closer access point is to the end, the greater impact harmonic voltage has on the system. Through altering fundamental voltage, access points make influence on the harmonic injection level. When access capacity does not exceed the total load capacity, voltage continues to drop along the line so that voltage connected to the head of line is higher than that at the end. Meanwhile, for the PV power with constant *PQ* model, fundamental current is smaller with the incensement of fundamental voltage. Hence, the smaller overall harmonic current injected into the PCC is caused by the closer position of photovoltaic power to the system bus. When access location is closer to the end of the line, conversely, harmonic current injected into the PCC is greater.

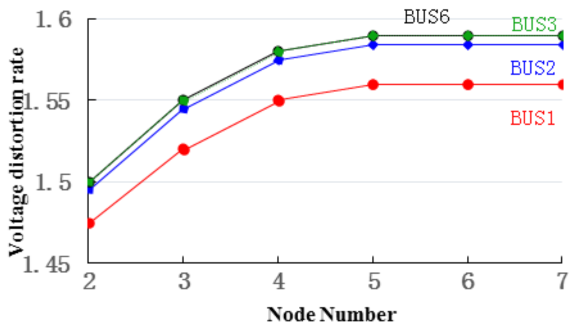

Figure 5. Total distortion rate under different access location.

5.4 Influence of dispersed mode on harmonics

Taking the actual needs of users and resource distribution issues into account, in the actual planning, it is extremely difficult to centralize distributed photovoltaic and other renewable energy sources in one load point. When energy sources own larger access capacity, they are usually distributed to each node. Case 3 was simulated under the condition that its decentralized mode was respectively set to be evenly, randomly (computer-generated random number), and in proportion of loading (the ratio of access capacity of the point to the total access capacity equal to the ratio of access load of the point to the total capacity of the load), Results of simulation are shown in Figure 6.

As can be seen from Figure 6, the overall level of harmonics in evenly distributed mode and in proportion of load is slightly higher than that in randomly distributed mode. There are two reasons for this phenomenon. For one thing, from the analysis by the access position that access location close to the system bus can drop the level of injected harmonics, the capacity of distributed power access to the head line is larger in random mode. For another reason, each PV inverter can be seen as a small harmonic source, and there is a superposition of harmonic relationship among the harmonic sources. When two harmonic sources are relatively close to each other, the phase angles may be more close to linear superposition. When the number of grid-connected points increases, it will appear the case that the phase angle is positive and negative offset, and harmonics is smaller than it is in the more decentralized access.

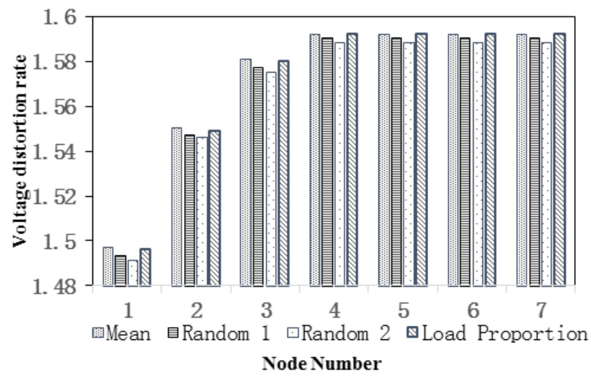

Figure 6. Total distortion rate under different dispersity.

5.5 Influence of cable capacitance on the system response characteristics

Simulate case 1 with harmonic source at the end of the feeder. Earth capacitance parameters of all cable lines are set to 0 firstly. Then observe the injection current, current in middle line and current inflow to the external network of each harmonic. The values are shown in Figure 7.

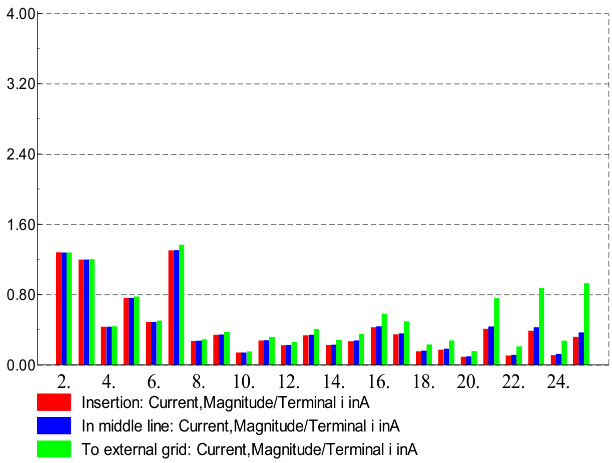

Figure 7. Harmonics in system without cable capacitance.

The capacitance parameter of cable lines is set to the actual value. The injection current, cut-line current and current in flow to the external network of each harmonic are shown in Figure 8.

Something can be drawn from Figure 8. On condition that the cable capacitance is out of consideration, parallel resonance can be realized when times of harmonic waves gets to over 25. And photovoltaic power harmonic times are mainly concentrated on 2-25 times, with 11 below and 25 above of that ignored especially. Therefore, resonance makes no significant effect on the overall harmonic amplification when the harmonic order of that is in 25 outside. As is shown in Figure 8, cable capacitance counted, the resonant point is migrated forward significantly, which extremely amplify the nearby 14th harmonics and harmonic current of resonance point wave is amplified to a certain value, rather than theoretical infinity, since the resistance value is not small enough to be ignored actually. Usually, filter channel is installed in frequency with larger harmonics, but the higher harmonics amplified after system response will also cause harm to the system. Therefore, you should also consider system characteristic and adjust series reactance ratio when setting the filter channel, so that the resonance point is within the minor harmonic bandwidth in [10].

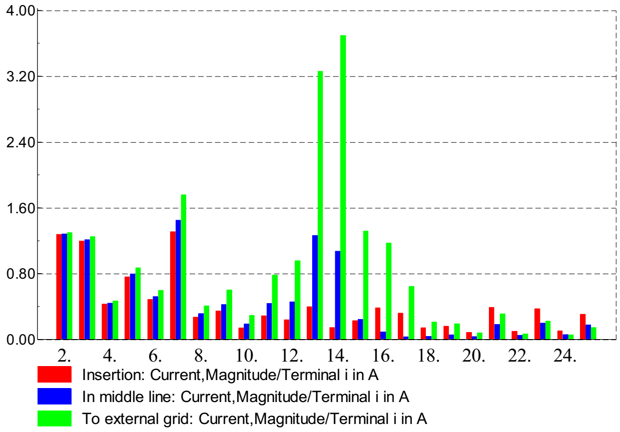

Figure 8. Harmonics in system without cable capacitance.

6 Conclusion

1) Cable line with specified length will result in amplification of harmonic waves around. To limit singular and high-order harmonic generation, filtering device is a need to install.

2) Keeping the capacity of the access invariant, the closer PV access location to the end of the line will also cause higher harmonic distortion level of distribution network. In order to reduce the harmonic distortion, the renewable energy can be considered being connected to the middle of node with heavy load, instead of the end of the lines.

3) After meeting the user's installation requirements and checking capacity of lines the position PV grid-connected should be controlled to be similarity, because counteraction between harmonic sources can assist in reducing the diffusion of harmonics, the verification of power capacity of line.

4) PV access makes value of 10-25 times of harmonics within the distribution network not be ignored. In case that some of the higher harmonics is amplified to damage grid security, not only injection characteristic of harmonics but the response characteristics of the system is to be considered when filter channel is to be set.

Currently, the paper only considered the inverter access. And with the development of renewable energy, there will be more types of power connected into distribution network, which will produce interaction, impact of which on distribution network harmonics remains to be further studied.

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