Research on transmission mechanism of harmonics in cable lines

Ling Pan1,*, Qian Feng1, Peng Zhang1, Bing Shen1, Ran Chen1, and Ping Zeng1

1State Grid Shanghai Electric Power Research Institute, Shanghai, China

*Corresponding author e-mail: 2423474554@qq.com

Abstract. The high cabled rate of urban power grid aggravates the risk of resonance and harmonic amplification. In addition, the system side of DC receiving end urban power grid contains converter station high-power harmonic sources, while the user side contains other nonlinear user harmonic sources. There are two-way conduction characteristics of harmonics in transmission lines. The problem of resonance and harmonic amplification in distribution network is aggravated by high cable ratio. Therefore, the response of the system side injected harmonic voltage at the end of the line and the potential harmonic amplification problem after the user side injected harmonic current are studied respectively. The influence of key factors (line type, length, load rate and power factor) on harmonic propagation is analyzed. The characteristic harmonic of converter station is not amplified and the most severe condition of amplification is summarized. The harmonic limit of the harmonic injection terminal is also proposed.

1. Introduction

In recent years, with the continuous development of urban and distribution network construction, overhead distribution lines and column equipment can not meet the requirements of modern people for urban environment and beauty. Power grid construction gradually uses underground power cable lines to replace overhead wires.

Compared with overhead line, cable has larger capacitance to ground, which is easy to produce inductance capacitance coupling with inductive components in power grid, resulting in resonance and harmonic amplification [1][2]. In addition, with the rapid development of power electronic technology, the power electronic rate of urban power grid is increasing, which leads to the complexity and diversification of harmonic sources in power grid, and also aggravates the harmonic pollution. The establishment of harmonic impedance model is the basis of studying harmonic amplification characteristics [3].

Therefore, the research on the distribution characteristics of harmonics in the whole cable power supply area can help to analyze the harmonic voltage and current distribution of each node and line, and has guiding significance for the prediction of resonance and harmonic amplification. In this field, the modal analysis method proposed by wilsun Xu in 2005 decomposes the node admittance matrix of the system into eigenvalues to identify the modal resonance frequency and node participation factor, so as to give the influence factor information leading to harmonic amplification and resonance [4][5]. It lays a foundation for the application of modal analysis in harmonic distribution characteristics. Since then, modal analysis has been applied to various practical engineering fields to study the harmonic distribution characteristics in different scenarios. For example, the modal analysis method is
applied to the dynamic resonance analysis of the full parallel at network, which effectively evaluates the resonance problems caused by the dynamic running locomotives in the traction network. In addition, modal analysis is applied to analyze the harmonic characteristics of wind farm system. The resonance problem of wind farm is studied, and the relationship between line length and harmonic amplification is analyzed. In the aspect of series resonance, the application of modal analysis is also studied, which is a supplement to the original modal analysis theory [6][7]. However, in the existing research, there is a lack of in-depth research on the harmonic conduction characteristics of the whole cable high power supply area.

However, the existing research is less focused on the propagation law of harmonics in cable lines. Due to the large capacitance of cable to ground, and compared with overhead line, its distributed parameter characteristics are more obvious, which may cause harmonic amplification and resonance in power grid. Therefore, it is necessary to analyze the propagation law of harmonic after cable injection in the whole cable supply area.

2. Study on the amplification law of harmonic after transmission through transmission line

2.1. Hyperbolic function model of transmission line

In the whole cable power supply area, due to the large ground capacitance of the cable, it is easy to cause inductive capacitive coupling with inductive components in the power grid. When harmonics are injected from the head end of the cable, harmonic amplification and resonance may occur at the end of the cable. Thus, even if the harmonic voltage at the first end of the line does not exceed the standard, the harmonic voltage at the end of the line may exceed the standard due to harmonic amplification.

Considering the distribution parameter characteristics of the line, the two port network of the line is established by hyperbolic function, as shown in Figure 1. When the voltage $U_{1f}$ and current $I_{1f}$ of the sending end (head end) at frequency $f$ are known, the voltage $U_{2f}$ and current $I_{2f}$ of the receiving end (end) at the distance from the sending end $l$ can be expressed as two port network

\[
\begin{bmatrix}
    U_{2f} \\
    I_{2f}
\end{bmatrix} = \begin{bmatrix}
    \cosh(\gamma l) & Z_c \sinh(\gamma l) \\
    \sinh(\gamma l) & \cosh(\gamma l)
\end{bmatrix} \begin{bmatrix}
    U_{1f} \\
    I_{1f}
\end{bmatrix},
\]  

(1)

Where, $\gamma = \sqrt{(r_h + jx_h)(g_h + jb_h)} = \alpha + j\beta$ is the propagation constant, while $\alpha = \alpha_0\sqrt{f/f_0}$, and $\beta = \beta_0\sqrt{f/f_0}$. $Z_c$ is the characteristic impedance of the line. Besides, $r_h$, $x_h$, $g_h$, and $b_h$ are respectively represents the resistance, reactance, conductance and susceptance per unit length of transmission line under H-th harmonic.

![Figure 1. Two port network model of harmonic propagation through transmission lines](image)

By complex expansion of hyperbolic function in equation (1), we have

\[
\begin{align*}
    \cosh(\gamma l) &= \cosh(\alpha l) \cos(\beta l) + j \sinh(\alpha l) \sin(\beta l) \\
    \sinh(\gamma l) &= \sinh(\alpha l) \cos(\beta l) + j \cosh(\alpha l) \sin(\beta l),
\end{align*}
\]  

(2)
Through the transformation shown in equation (2), the two port model in complex form in equation (1) can be transformed into the two port model in real form for further analysis.

2.2. Research on transmission model of harmonic voltage injection line system

For the two port model shown in Figure 1, when the harmonic voltage is injected from the system side of the line, considering the characteristics of the line distribution parameters, the harmonic amplification phenomenon may appear at the end of the line. Thus, even if the harmonic voltage content at the line harmonic injection end does not exceed the standard, the harmonic voltage at the line end may exceed the standard. Therefore, it is necessary to study the amplification law of harmonic voltage at the end of transmission line.

According to the voltage level and power factor, the load impedance at the end of the line can be built by using the CIGRE model shown in Figure 2. The impedance of each part is shown in equation (3).

\[
\begin{align*}
R &= \frac{U_n^2}{P_n} \\
X_s &= j0.073hR \\
X_p &= j\left(\frac{hR}{6.7\frac{Q_n}{P_n} - 0.74}\right)
\end{align*}
\]

Where: \( U_n \) represents the rated voltage of the bus under the fundamental wave; \( h \) is the harmonic number; \( P_n \) is the active power of the load; \( Q_n \) is the reactive power of the load.

For the load impedance, we have

\[
U_{zf} = I_{zf}Z_k, \quad (4)
\]

Thus, according to equations (1) and (4), the transfer function of the harmonic voltage injection at the first end of the line to the harmonic voltage at the end of the line can be obtained as

\[
H_{uu} = \frac{U_{zf}}{U_{1f}} = 1 \frac{Z_c}{Z_R}\cosh(\gamma l) + \frac{Z_c}{Z_R}\sinh(\gamma l), \quad (5)
\]

Setting \( n = Z_c / Z_l = a - jb \), where \( |n|^2 = a^2 + b^2 \), we have
where,

\[ \mu = \beta l. \] (7)

By simplifying equation (6), the equivalent calculation model of the transmission coefficient of the terminal voltage when the line harmonic voltage is injected at the first end can be obtained

\[ |H_{uu}| = M_{uu} / \sqrt{A_{uu} \sin (2\mu + \varphi) + B} = M_{uu} / \sqrt{T_{uu}}, \] (8)

where,

\[ \begin{cases} A_{uu} = \sqrt{(1 - |\eta|^2)^2 / 4 + b^2}, \\ M_{uu} = 1 \end{cases} \] (9)

and

\[ \begin{cases} B = \left( (1 + |\eta|^2) / 2 \right) \cosh (2\alpha l) + \alpha \sinh (2\alpha l), \\ \varphi = \arctan \left( (1 - |\eta|^2) / (2b) \right) \end{cases} \] (10)

When the key influence factors such as line type (cable or overhead line), line length, load rate and power factor change, the propagation law of harmonics in the line will also be affected. Therefore, it is necessary to analyze the effect of key factors on the harmonic propagation law in combination with the actual engineering situation.

In addition, harmonic voltage amplification may occur at the end of the line after injecting harmonic voltage into the system side of the line, so it is necessary to analyze the harmonic voltage limit at the injection end of the line according to the characteristic harmonics of the converter station. Although the harmonic voltage at the first end of the line does not exceed the standard, the harmonic voltage at the end of the line will exceed the standard due to amplification.

3. Research on the law of harmonic propagation after amplification

The propagation law of harmonics in 220kV cable and overhead line is analyzed. The line length is gradually increased from 20km to 100km for simulation. The terminal load is set at 160mva and the power factor is 0.9.

The length of the cable gradually changes from 20km to 100km, and the amplification and attenuation of harmonic voltage at the end of the line is shown in Figure 3. When the cable length is 20km, there is a peak value of harmonic amplification near the 30th harmonic at the end of the line. For the 25th and 25th characteristic harmonics near the converter station, the amplification factor is 3.3 and 4.1 times respectively; when the line length is 40km, the harmonic amplification peak is located at 15.6 times, and the corresponding harmonic voltage amplification factor is 13.5 times. When the line length is 60 km, the peak value of harmonic amplification is 10.6 times, and the...
corresponding harmonic voltage amplification is 9 times. The amplifications of the 11th and 13th characteristic harmonics are 7.2 and 2.4 times respectively. When the line length is 80 km, there are two harmonic amplification peaks at 22.3 times and 37 times respectively, corresponding to 15.4 times and 23.5 times of harmonic voltage amplification. The amplifications of the 23rd, 25th, 35th and 37th characteristic harmonics are 6.7, 1.8, 2.5 and 22.3 times, respectively.

**Figure 3.** Amplification of terminal harmonic voltage after cable length change

After the cable length changes, the corresponding harmonic voltage amplification factor at each frequency is shown in Figure 4.

**Figure 4.** Relationship between harmonic voltage amplification and cable length

Compared with the overhead line, when the cable length changes, the harmonic voltage amplification peak value is more and the frequency range is wider. When the length of the cable changes, the characteristic harmonics of 11th, 13th, 24th, 25th, 35th and 37th order in the converter station may appear the peak value of harmonic voltage amplification. In practical engineering, according to the length of the line, the characteristic harmonic voltage of the cable system side should
be limited to a lower level to prevent the harmonic voltage amplification at the end of the cable from exceeding the standard.

4. Conclusion

In this paper, considering the distribution parameter characteristics of cable lines, the bi-directional conduction law of harmonics in the line of receiving end DC urban power grid full cable power supply area is studied. Since the system side of the line contains high-power harmonic sources such as converter station, the harmonic voltage may be amplified at the user side of the cable after the harmonic voltage is injected from the cable line. The effects of key factors such as line type (overhead line or cable), line length, load rate and power factor on the harmonic conduction law are analyzed. In addition, in the same frequency band, the frequency of peak value will increase; when the load rate increases, the peak value of harmonic voltage amplification at the end of the line will move to the high frequency direction, and the peak value will decrease; in contrast, the power factor increases. When the power factor increases, the peak value of harmonic voltage amplification at the end of the line will move slightly to the low frequency direction, and the amplitude will decrease slightly. In addition, for the characteristic harmonics generated by the converter station harmonic source, the maximum harmonic voltage amplification factor at the end of the line under severe conditions and the length range of the line to ensure no harmonic amplification are analyzed respectively.

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