Determination of Optimal Installation Point of APF Based on Selective Harmonic Compensation

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Abstract. There is a large number of uncertain harmonic sources and background harmonics in the distribution network. Due to the function of the system node admittance matrix, the installation position of the filter has a significant impact on the harmonic control effect. In this paper, we aim to reduce the current distortion rate of the distribution network and optimize the optimal installation position of the active filter. Based on the principles of harmonic active/reactive power division and the relationship curve between the injection compensation current of each bus and the distortion rate, if the value of the current distortion rate meets the national standard requirements, we can obtain the compensation status of each bus filter for each harmonic and the corresponding compensation current. The bus with the smallest injected compensation current is the optimal installation location of the active filter. Simulation results by Matlab/Simulink verify the feasibility of the method. The results show that on the premise that the distortion rate meets the requirements of grid connection, the capacity of the filter is reduced, and the better economic efficiency is achieved.

Key words: Power distribution network; Active power filter; Optimizing installation position; Active component of harmonics; Reactive component of harmonic

1. Introduction

With the extensive application of various types of power electronic devices in electrical equipment, a large amount of harmonic current is injected into the distribution network directly connected to users, which is the main source of harmonics in the distribution network[1-3]. The single capacity of electrical equipment is small, but the cumulative number of equipment in the power grid is large and widely distributed. The harmonics are injected into the distribution network from less and more, which causes greater pollution and harm to the power grid. At present, the main research focus of APF (active power filter) is on the near compensation of active power filters for deterministic
harmonic sources[4]. APF (active power filter) is installed in a suitable location, which can not only reduce harmonic current. In order to make the grid-connected current distortion rate meet the requirements of the national standard and reduce the capacity of the filter, the installation position of the active filter and the selection of the filter compensation method are also extremely important[5-6].

In terms of optimizing the installation position of the filter, literature[7] proposed that installing the filter at the end of the distribution network bus can obtain better compensation performance and certain safety, but this method is only suitable for some simple networks. When it encounters a more complex network, it cannot achieve better governance effects. Reference[4] analyzes the frequency response characteristics of the distribution network on the basis of the simplified model of the distribution network, observes the voltage response sensitivity of each bus by injecting the same amount of current, and thus obtains the bus with a larger voltage response sensitivity as Optimal installation point. However, for complex distribution networks, this method is difficult to find the only installation point. Reference[8] solves the optimal installation point of the APF in the distribution network by using mixed integer mathematical programming method, decomposing the problem into main problems and sub-problems, and iteratively solving, and using the Lagrange multiplier method to obtain the optimal Solution, but considers several major variable constraints in the power grid, and does not consider all variables and the interaction between variables[9].

This paper proposes a selective compensation method based on harmonic currents to determine the optimal installation point. When we find multiple installation points based on the literature[4], or based on the experience of nearby compensation, the nonlinear load Several busbars are used as candidates for installation points. Then install APF with separate compensation for harmonic active and reactive power at these candidate points to obtain the compensation status of the filter for each harmonic and the corresponding compensation current, fitting the relationship between the compensation current and the current distortion rate Curve, take the distortion rate when the current distortion rate of the distribution network reaches the grid connection requirement, get the compensation status of each bus filter for each harmonic, and then compare the compensation current injected by each APF. That bus is the optimal installation point for APF. The optimal installation point selected by this method considers all factors that can generate harmonics, and takes into account the interaction of these factors, and finally obtains the optimal installation point. This method has general applicability and is suitable for networks with various nonlinear loads. The results of simulation examples verify the effectiveness of the proposed scheme and find the optimal installation point. While meeting the requirements of network access, it can also Reducing the capacity of APF makes APF more economical.

2. Objective function of harmonic control in distribution network

The harmonic currents are generated by non-linear loads in the distribution network, which leads to distortion of the bus voltages in the power grid. According to the relevant regulations in GB/T14549-1993, the user terminal must reduce the total distortion rate of the grid-connected harmonic current go to the national standard[10], so this paper uses the total current distortion rate of the distribution network bus as the harmonic control objective function. Define a network with N nodes, the harmonic current distortion rate of node n:
The standard distribution divides the number of harmonic points, the sum of which equals the constant power of the working paper. The current compensation can be separate active/reactive components, and the APF can be installed at the busbar controller. The current installation is found, and the compensation is of the highest rate. In practice, the working condition of APF is a passive working state. The harmonic current of the bus is detected first, and then a compensation component of equal size and opposite direction or polarity is generated by the controller, so that the compensated component and the APF produce The compensation components cancel out, so that the grid current becomes a sine wave current again. The load of different busbars in the distribution network is different, so the harmonic currents are also different. Therefore, when the ordinary APF is installed, the distortion rate of the total busbar becomes smaller after compensation, but the APF installed on different busbars is injected. The compensation currents are also inconsistent, so it is impossible to compare which bus is the optimal installation point. When we use filters with separate compensation of active and reactive power for harmonics of different orders, the compensation of each harmonic can be subdivided to obtain a gradient compensation curve, and so on, we can get each The busbars correspond to different compensation curves, so taking the same output value and the same total current distortion rate can get the compensation status of each harmonic when the APF is installed in each busbar, and at the same time, it can also be obtained that the APF is injected into each busbar compensation current, the bus with the smallest compensation current is the optimal installation point of APF.

This paper uses APF with selective compensation of active/reactive harmonic current. By dividing the active/reactive power of each harmonic, the compensation amount of the filter can be subdivided. By adjusting the APF for each harmonic compensation state, the relationship curve between the injection compensation current and the distortion rate of each bus is obtained, and the injection compensation current when the same distortion rate of each bus is found is found. The smaller the compensation current is the ideal installation point. Therefore, the key lies in how to find

\[ I_{THDN} = \sqrt{\sum_{h=2}^{H} \left| I_{h} \right|^2 / \left| I_{1} \right|^2} \]

(1)

Where \( h \) is the number of harmonics; \( n \) is the number of the bus of the power grid, \( H \) is the number of the highest harmonic in the harmonics, and \( I_{h} \) is the \( h \) harmonic current of node \( n \). \( I_{1} \) is the fundamental current of node \( n \). The purpose of harmonic control is to obtain a better harmonic control effect when the minimum compensation current is injected, not only to reduce the harmonic distortion rate below the national standard, but it can also reduce the effect of filter capacity. Therefore, the objective function of harmonic control is defined as:

\[ f(I_{c}) = \sum_{n=1}^{N} (I_{THDN})^2 = \sum_{h=2}^{H} \sum_{n=1}^{N} \frac{|I_{h}|^2}{|I_{1}|^2} \]

(2)

Where \( I_{c} \) is the current injected by the filter into the grid bus for compensation.

3. Solution method of optimal installation position

In this paper, first, according to the frequency response of the distribution network or according to the principle of nearby installation, several busbars with large nonlinear loads are used as candidates for installation points, and then this method is used to select the optimal installation point from these alternative installation points. In practice, the working condition of APF is a passive working state. The harmonic current of the bus is detected first, and then a compensation component of equal size and opposite direction or polarity is generated by the controller, so that the compensated component and the APF produce The compensation components cancel out, so that the grid current becomes a sine wave current again. The load of different busbars in the distribution network is different, so the harmonic currents are also different. Therefore, when the ordinary APF is installed, the distortion rate of the total busbar becomes smaller after compensation, but the APF installed on different busbars is injected. The compensation currents are also inconsistent, so it is impossible to compare which bus is the optimal installation point. When we use filters with separate compensation of active and reactive power for harmonics of different orders, the compensation of each harmonic can be subdivided to obtain a gradient compensation curve, and so on, we can get each The busbars correspond to different compensation curves, so taking the same output value and the same total current distortion rate can get the compensation status of each harmonic when the APF is installed in each busbar, and at the same time, it can also be obtained that the APF is injected into each busbar compensation current, the bus with the smallest compensation current is the optimal installation point of APF.
the relationship curve between injection compensation current and distortion rate. In this paper, the harmonics on the load side are selectively compensated for the harmonics on the load side. Set the harmonic current content $I_H$ of the grid bus.

$$I_H^2 = \sum_{h=2}^{\infty} (I^h)^2$$

$$I^h = (I_p^h)^2 + (I_q^h)^2$$

Where $I^h$ is the current of the h-th harmonic of the bus L, $I_p^h$ is the active component of the h-th harmonic, and $I_q^h$ is the reactive component of the h order harmonic.

The working principle of APF is to generate a compensation component that is equal to the compensation component in the opposite direction, so that the compensated component and the component generated by the filter cancel each other. $I_c^h$ is the compensation current for the h order harmonic, and its value can be expressed as:

$$I_c^h = \begin{cases} 
I_c^h & \text{if } \phi_h^t = 0, \\
0 & \text{if } \phi_h^t = 1.
\end{cases}$$

The method proposed in this paper is to install APF in the alternative bus, and control the compensation current of the filter to make the total bus distortion rate consistent. Compare the injection current of the filter installed on the alternative bus, the bus with the smaller injection current is Optimal installation of busbars.

Therefore, how to control the compensation current of the APF is the key to find the optimal installation point. It is known that the main harmonics in the power grid have 5, 7, 11, 13 and other odd harmonics, so the APF on the bus is The operating state of the wave can be expressed as:

$$X_L^h = [x_p^h, x_q^h]$$

Where $X_L^h$ represents the operating state of the filter on the bus L to the harmonic of the h-th order, when $x_p^h = 1$, it represents the compensation of the active power component of the harmonic of the h-th order. When $x_p^h = 0$, it means that the active component of the h-th order harmonic is not compensated; when $x_q^h = 1$, it means that the reactive component of the h-th order harmonic is compensated; when $x_q^h = 0$, it indicates that the reactive component of the h-th order harmonic is not
make compensation.

The operating state of the filter on bus L for harmonics is:

\[ X_L = \sum_{h=2}^{H} X_L^h \]  (7)

The state of the filter of the entire network can be expressed as:

\[ X_Z = \sum_{L=1}^{N} \sum_{h} X^h \]  (8)

A function is expressed as follows:

\[ Y_{THD_i} = f(X^1_L, X^2_L, \ldots, X^n_L) \]  (9)

A multiple linear regression model is established according to the function:

\[
\begin{align*}
Y &= \beta_0 + \beta_1 X^1_L + \beta_2 X^2_L + \cdots + \beta_n X^n_L + \varepsilon \\
\varepsilon &\sim N(0, \sigma^2)
\end{align*}
\]  (10)

\( \beta_0 \) is the background harmonic, and \( \beta_1, \beta_2 \ldots \beta_n \) is the partial regression coefficient, which represents the effect of the operating state on the L bus on the total bus distortion rate, which is \( \varepsilon \) random error.

Carry out \( n \) independent observations to record the compensation status of the filter installed on the bus for each harmonic. If the 5th harmonic is fully compensated on the L bus, the 5th harmonic only compensates the active part, corresponding to X can expressed as:

\[ X^5_L = [1, 1], X^5_Z = [1, 0] \]  (11)

\( n \) independent observations are written in matrix form:

\[ Y = X\beta + \varepsilon \]  (12)

\[ \varepsilon = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n), \]

\[ \beta = (\beta_0^i, \beta_1^i, \ldots, \beta_n^i), \]

The corresponding compensation state matrix is:

\[ X = \begin{bmatrix}
1 & x_1^1 & x_2^1 & \cdots & x_n^1 \\
1 & x_1^2 & x_2^2 & \cdots & x_n^2 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & x_1^n & x_2^n & \cdots & x_n^n 
\end{bmatrix} \]  (13)

In this paper, the appropriate value \( \beta \) for solving the regression coefficient should minimize the sum of squares of the residuals,
\[ Q = \sum_{i=1}^{n} \bar{g}_{i}^2 = \sum_{i=1}^{n} (y_{i} - \hat{y}_{i})^2 = \sum_{i=1}^{n} (y_{i} - \hat{\beta}_{i} x_{i} - \hat{\beta}_{i} x_{i} - \cdots - \hat{\beta}_{n} x_{n})^2 \quad (14) \]

According to Least Squares Theory, Equation (15) finds the partial derivative of \( \beta \) so that the partial derivative is zero, that is:

\[
\frac{\partial Q}{\partial \hat{\beta}_{i}} = -2 \sum_{i=1}^{m} (y_{i} - \hat{\beta}_{0} x_{i} - \cdots - \hat{\beta}_{n} x_{n}) = 0 \\
\frac{\partial Q}{\partial \hat{\beta}_{n}} = -2 \sum_{i=1}^{m} (y_{i} - \hat{\beta}_{0} x_{i} - \cdots - \hat{\beta}_{n} x_{n}) x_{n} = 0 \\
\vdots \\
\frac{\partial Q}{\partial \hat{\beta}_{n}} = -2 \sum_{i=1}^{m} (y_{i} - \hat{\beta}_{0} x_{i} - \cdots - \hat{\beta}_{n} x_{n}) x_{n} = 0
\quad (15) \]

Solve for \( \hat{\beta}_{i}(0, 1, \ldots, n) \) and get the fitting function, so when a given value is input, that is, the distortion rate of the total bus of the network, the operating state of each harmonic in the harmonic current of a set of filters can be obtained, and then adjust the APF pair. Each time the harmonics are compensated, the magnitude of the injected current on the bus L can be obtained, and the compensation current injected on each candidate bus is compared. The smaller the compensation current is the optimal installation point.

The prerequisite for completing the above work is the detection of the active and reactive components of the single harmonic current in order to selectively compensate for the harmonics, thereby obtaining a series of compensation states and corresponding compensation results. It is the basic work to find the compensation curve of each bus.

4. Harmonic current active component and reactive component detection

According to the previous analysis, the key to finding the optimal installation point in the network is to subdivide the compensation current. The method proposed in this article is to detect the active/reactive current of each harmonic. The compensation current is subdivided, and the gradient compensation curve of the corresponding bus is obtained. According to the principle of any harmonic active/reactive current detection derived from the instantaneous power theory, the harmonic current vector is the active component \( I_{kP} \) of the harmonic current only if it corresponds to the projection on the harmonic voltage vector of the same order.

![Figure 1. Vector graph of k-times harmonic current and voltage component](image)

As shown in Figure 1, it is obvious that \( I_{kq} \) and \( I_{kd} \) in Figure 1 are not the active and reactive components corresponding to the harmonic current, but the harmonic compensation device uses \( I_{kd} \)
as the active component to compensate, so the rotating d-q coordinate system must be used. It is coaxial with the harmonic voltage vector $\bar{U}_K$, so that the projection of the harmonic current on the d axis is the current active component $I_{KP}$, and the corresponding component of the q axis is the reactive component $I_{KQ}$ of the current. According to Figure 2, the initial phase $\varphi_{UK}$ of the k-th harmonic voltage can be obtained.

$$\varphi_{UK} = \arctan \left( \frac{U_{kd}}{U_{kd}} \right)$$  \hspace{1cm} (16)

The current in Equation (16) can be obtained through the low-pass filter to obtain the active component $I_{KP}$ and reactive component $I_{KQ}$ of the k-th harmonic current.

![Flow chart for optimal installation point solution](image)

**Figure 2.** Flow chart for optimal installation point solution

Then, according to the inverse transformation matrix corresponding to the generalized park transformation matrix $T_K$, the d-q to abc coordinate system can be transformed into equation (17), that is, the active and reactive components of the K-th harmonic under the three-phase system.

$$\begin{align*}
I_{KP} &= \sqrt{3} I_K \cos(-\varphi_{UK} + \varphi_{IK}) \\
I_{KQ} &= \sqrt{3} I_K \sin(-\varphi_{UK} + \varphi_{IK})
\end{align*}$$  \hspace{1cm} (17)
\[
\begin{align*}
I_{LKP} &= \sqrt{2}I_k \cos(kwt + \varphi_{UK}) \cos(-\varphi_{UK} + \varphi_{IK}) \\
I_{LQ} &= \sqrt{2}I_k \sin(kwt - \varphi_{UK}) \cos(-\varphi_{UK} + \varphi_{IK})
\end{align*}
\] (18)

From equation (18), the active and reactive components of a single harmonic can be obtained. In the distribution network, the main harmonics are 5, 7, 9, 11 and other 6n ± 1 order harmonics, but different order harmonics. The proportions are also different, that is, they have different weights, so the compensation of APF can be subdivided, and the subdivision can be achieved by separately compensating the active and reactive power, and different compensation states are adopted for the active and reactive power of each harmonic. You can get a series of compensation results and total bus current distortion rate, then according to the method described above, a fitting function is obtained from these data, and finally according to the total bus distortion rate allowed by the national standard, the filter is calculated for different harmonics. The active and reactive power compensation state of the wave can be used to obtain the injection compensation current of the APF. Comparing the compensation current injected when different busbars reach the same distortion rate, the optimal installation point of the filter can be obtained.

5. Simulation analysis

In order to test the correctness of the method mentioned in this article, according to a factory's distribution network wiring diagram, it is simplified to get 10 bus distribution network, grid power supply 10KV, the remaining branches are connected with 10KV/0.4KV transformer, followed by various Rectifiers and equipment. Connect the circuit as shown in Figure 3.

![Figure 3. Circuit diagram of distribution network](image)

The power supply consists of an ideal power supply, with non-linear loads connected to each bus. The main harmonics are the fifth, seventh, eleventh, thirteenth, and nineteenth harmonics. By establishing a voltage transfer matrix and a current transfer matrix, and analyzing their frequency responses, the easily resonant branches 1, 6, 8 are obtained, and then the APF mentioned in this article is connected to the busbars outside these branches. By adjusting the different compensation states for each harmonic, a set of corresponding compensation results is obtained.

The neural network toolbox in MATLAB is used for fitting. In the three-phase system, the main harmonics are 5, 7, 11, 13, 17, 19 harmonics. Taking bus 2 as an example, it can be properly installed
on bus 2, the total bus current distortion rate:

\[
y_{rhd}^2 = \beta_5^2 + \beta_4^2 X_2^4 + \beta_7^2 X_2^7 + \beta_9^2 X_2^9
+ \beta_1^2 X_2^{11} + \beta_2^2 X_2^{13} + \beta_3^2 X_2^{15} + \beta_6^2 X_2^{19}
\]

(19)

The expression of the distortion rate function of other busbars can also be obtained. Find the compensation status of each harmonic on the APF on each bus when the distortion rate is consistent. The corresponding output compensation current can be obtained. It can be concluded that the total bus current distortion rate before and after HAPF is connected to each bus is shown in Table 1. From the analysis in Table 1, we can see that because the control curve is discrete, the distortion rate of the total bus can not be completely controlled uniformly, and can only be replaced by an approximate value, but the result also has certain authenticity. From the table, we can see that when we According to the function expression, the compensation status of APF for each harmonic when the total bus distortion rate is 5% is obtained. Calculate the injected compensation current. It can be seen that when the APF is installed on the bus 4, the injection current is the smallest, which indicates that the bus 4 is the optimal installation point, indicating that when the harmonics are treated, a smaller compensation current can be injected at this place to achieve a better treatment effect. Which not only meets the national requirements for the distribution network, but also reduces the capacity of the filter.

**Table 1.** The current injected by HAPF when the bus reaches the same distortion rate

| bus | Bus distortion rate % | Injected current of APF /A |
|-----|------------------------|---------------------------|
| 2   | 4.95                   | 6.25                      |
| 3   | 4.85                   | 9.45                      |
| 4   | 5.04                   | 3.44                      |
| 5   | 4.99                   | 5.64                      |
| 6   | 5.20                   | 6.31                      |
| 7   | 5.15                   | 8.15                      |
| 9   | 5.22                   | 6.57                      |
| 10  | 5.03                   | 9.75                      |

It can be seen from the node admittance matrix that changing the value or position of the injected current will cause the change of the harmonic current of the node in the distribution network, so when the APF is installed on the bus 4, the current distortion rate of each bus before and after the filter is connected is shown in Table 2. As shown. At this time, the compensation current injected into the bus 4 contributes to the current harmonic distortion rate of each bus.

**Table 2.** Harmonic content of bus before and after HAPF installation

| bus | Distortion rate before compensation % | Injected current of APF /A |
|-----|---------------------------------------|---------------------------|
| 1   | 6.81                                  | 3.52                      |
| 2   | 3.52                                  | 1.62                      |
| 3   | 6.31                                  | 3.21                      |
| 4   | 6.44                                  | 1.02                      |
The simulation waveform when APF is installed on bus 4 is shown in Figure 4. In the simulation, APF is connected at 0.2 seconds. By comparing the total bus current waveform before and after APF input, it can be found that before the filter compensation, the current waveform distortion is serious. After the filter is put into use, the waveform is larger and improved, which is similar to a sinusoidal waveform, indicating that APF has a good compensation effect, achieves the expected effect, and also meets the characteristics of the optimal installation point, that is, the minimum injection compensation current.

![Figure 4](image)

**Figure 4.** The current waveform before and after the HAPF is installed on bus 4

Before installing APF on bus 4, the total bus distortion rate is shown in Figure 5. It can be obtained by FFT analysis that there are many 5, 7, 9, 11 harmonics in the system. At this time, the total bus current distortion rate is 12.79%. After installing APF on bus 4, it meets the requirements of 5% of the national standard. As shown in Figure 6, the current distortion rate of the total bus is 5.04%, and the amount of 5, 7, 9, and 11 harmonics is greatly reduced to achieve the desired effect.

![Figure 5](image)

**Figure 5.** Current harmonic distortion rate of the main bus before HAPF installation
Figure 6. Current harmonic distortion rate of the main bus after HAPF installation

It can be seen from the above chart that the optimal installation point found according to the method proposed in this article not only satisfies the effect of harmonic control, but also reduces the compensation current output by the filter, making the filter more economical. And the results of experimental simulation and analysis are consistent, which shows the feasibility of this method to find the most superior.

6. Conclusion

The method proposed in this paper is to install APF on the bus of the distribution network. On the premise of meeting the national standard, by analyzing the frequency response characteristics of the distribution network, the basic bus with obvious response characteristics is used as an alternative installation point, and then use active and reactive power to separate Compensation characteristics, and then through multiple linear regression fitting, find the weight of active and reactive power in each harmonic, and obtain the corresponding relationship, which can be obtained while achieving the same compensation effect, the point where the minimum compensation current is injected, namely In order to install the bus bar optimally, and make the total bus current distortion rate meet the requirements of the grid connection, this can also reduce the capacity of the APF and make the filter more economical. Through the simulation model built by Matlab, the method described in this article is simulated and verified, and the theoretical feasibility of the method is verified.

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