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Comprehensive analysis on three-phase imbalance management technology of low-voltage distribution network

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Abstract. Energy production and use is one of the major sources of global greenhouse gas emissions. To combat climate change, many countries and organizations are pushing to reduce the use of fossil fuels, and the use of renewable energy sources such as solar, wind, and hydro is growing rapidly. The conversion of these renewable energy into electricity requires a large amount of power electronics. Power electronics have higher energy conversion efficiency, greater adjustability and control, and smaller size and weight than traditional generators. These characteristics make power electronic equipment have a wide range of application prospects in the field of energy conversion and power control. There may be cost, reliability, debugging, and three-phase imbalance issues. Based on the harm of three-phase imbalance to the economic operation and safe and stable operation of distribution network, the importance of three-phase imbalance in low-voltage distribution network is expounded, and the relationship between three-phase unbalance current and power factor is elaborated on the construction of three-phase imbalance. Reduce the harm of three-phase imbalance to the distribution network and reduce the loss of distribution network lines.

Keywords: Three-phase unbalance, unbalanced current, power factor, load compensation device.

1. Introduction

Energy production and use is one of the major sources of global greenhouse gas emissions. To combat climate change, many countries and organizations are pushing to reduce the use of fossil fuels, and the use of renewable energy sources such as solar, wind, and hydro is growing rapidly. The conversion of these renewable energy into electricity requires a large amount of power electronics. Power electronic equipment has the characteristics of high efficiency, adjustability, fast response, reliability, high power density and digital intelligence, making it play an important role in the field of energy conversion and power control. Power electronics have higher energy conversion efficiency, greater adjustability and control, and smaller size and weight than traditional generators [1-3]. These characteristics make power electronic equipment have a wide range of application prospects in the field of energy conversion and power control. There may be cost, reliability, debugging, and three-phase imbalance issues.

The quality of electrical energy is usually characterized by indicators such as frequency, offset, fluctuation, flicker, intermittent, collapse, spike, harmonic, distortion, three-phase imbalance, and high-frequency interference of the supply voltage. Three-phase imbalance is one of the important indicators

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of power quality. There are various imbalances in the power system, which can be summarized into two categories: accident and normality. Accidental imbalance is caused by system failure, this operating condition is not allowed in the system, generally through the protection device to cut off the faulty components, after treatment, then restore the system operation. Normal imbalance is caused by asymmetry of three-phase elements, line parameters or loads, such as traction loads in electrified railways, electric arc furnaces in smelting systems, etc. Normal imbalances allow for long-term or considerable periods of time to exist [3-6].

The more unbalanced the three-phase load, the unstable current will be generated, affected by the resistance, the power loss in the line will increase, resulting in the waste of electric energy resources; the capacity of the distribution transformer is designed according to the three-phase load balance state calculation, if the load is unbalanced, the transformer winding can only work according to the maximum load of one of the phases, which causes huge pressure on the transformer operation; the three-phase load is unbalanced will produce zero-sequence current, and the magnet core in the transformer will inevitably generate zero-sequence magnetic flux, and the current on the high-voltage side and the low-voltage side is not equal, resulting in excessive temperature of the transformer structural parts, which is bound to endanger the safety of the transformer; if the three-phase load is unbalanced, it will cause zero drift and output asymmetric voltage When the three-phase load is unbalanced, positive sequence, zero sequence, negative sequence and other currents will be generated, but the existence of zero sequence and negative sequence current will affect the accuracy of the energy meter [6-10].

In order to make the three-phase in the low-voltage distribution network in a balanced state, the three-phase voltage source must have the same frequency and amplitude in the sine wave and the phase angle is located at 120 degrees, under which the low-voltage distribution network can stably bring people to produce and use electricity. However, this situation is ideal, power quality and three-phase electrical balance is directly related, if the three-phase load is unbalanced, which in turn affects the power of the electric energy, the line voltage will also be affected. In light loads, the voltage of single-phase user energy will rise and cause damage to household appliances. Cause unnecessary economic losses.

Three-phase electrical imbalance, as shown in Figure 1, will bring related harm, stable three-phase imbalance is of great significance, this article mainly discusses the content of a brief introduction.

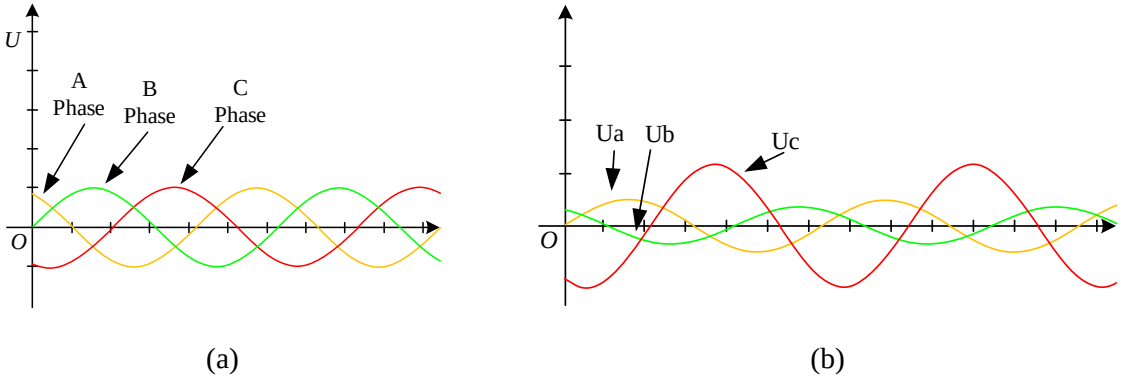

Figure 1. Waveform of difference phase conditions [2]. (a) Balanced. (b) Unbalanced.

2. Three-phase imbalance

On the issue of three-phase imbalance in distribution networks, scholars at home and abroad have carried out a lot of research, showing that imbalance refers to the different amplitudes of three-phase voltage (or current) in the distribution network or the phase difference is not 120°. As one of the power quality evaluation indicators, three-phase imbalance is usually used to express the degree of three-phase imbalance in the distribution network, the higher the unbalance, the worse the power quality, and vice versa.

There are many calculation methods for three-phase voltage imbalance at home and abroad, and the calculation of three-phase voltage imbalance in China's national standard is to decompose the phase

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voltage vector into positive and negative sequence components, and finally obtain the three-phase voltage imbalance through the ratio of the rms value of the two

$$\varepsilon_u = \frac{u_2}{u_1} \times 100\% \tag{1}$$

where ε is the three-phase voltage imbalance, U1 is the root mean square value of the positive sequence component, and U2 is the root mean square value of the negative sequence component.

Compared with the three-phase voltage imbalance, there are also several calculation methods for the three-phase current imbalance, and the commonly used calculation formulas in actual engineering are as follows

$$\varepsilon_i = \frac{i_{\max} - i_{\min}}{i_{av}} \times 100\% \tag{2}$$

where Imax is the maximum current value, Imin is the minimum current value, and Iav is the current average.

There are many calculation methods for three-phase voltage imbalance at home and abroad, and the calculation of three-phase voltage imbalance in China's national standard is to decompose the phase voltage vector into positive and negative sequence components, and finally obtain the three-phase voltage imbalance through the ratio of the rms value of the two,

$$\varepsilon_u = \frac{u_2}{u_1} \times 100\% \tag{3}$$

3. Analyze the relationship between three-phase unbalanced current and power factor

The three-phase currents are not equal, but have the same power factor. Its unbalanced additional line loss is calculated as

$$\Delta p = \frac{(I_a - I_b)^2 + (I_b - I_c)^2 + (I_c - I_a)^2}{3} \times R + I_0^2 R_0 \tag{4}$$

The three-phase currents are equal, but the power factors are not the same. Its unbalanced additional line loss is calculated as:

$$\Delta p = 3i_\alpha^2 R \left\{1 - \frac{1}{9}[3 + 2\cos(\phi_b - \phi_a) + 2\cos(\phi_b - \phi_c) + 2\cos(\phi_c - \phi_a)]\right\} + I_0^2 R_0 \tag{5}$$

The three-phase currents are not equal, and the power factors are not the same. Its unbalanced additional line loss is calculated as follows:

$$\Delta p = \frac{(I_a - I_b)^2 + (I_b - I_c)^2 + (I_c - I_a)^2}{3} \times R + I_0^2 R_0 \tag{6}$$

It can be seen from the above formula that the three-phase voltage balance can also reduce line loss, and the number is considerable, and the method is simple, which has become an important measure to reduce line loss in the power system, and has achieved good economic benefits.

4. Construction of three-phase load imbalance optimization model for low-voltage distribution network

Considering that there are certain dynamic and random characteristics of the electricity load, under normal circumstances, the three-phase load balance state is difficult to exist for a long time, and there is no absolute equilibrium. Therefore, an optimization model is constructed to reduce the imbalance by mediating the phase sequence. Before building an optimization model, it is necessary to clarify the relationship between user load and imbalance. Assume that the power load of sub-item Φ(Φ ∈ {B,C,D}) is PΦ, the power factor of distribution network operation is cosφ, and the average phase voltage is UΦ in the t time period. On this basis, the average split current is calculated as

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$$I_{\phi} = \frac{P_{\phi}}{U_{\phi} t \cos\varphi} \tag{7}$$

In Equation: IΦ represents the average split-phase current. Assume that the average load current of B term IB, the average load current of term C is IC, the average load current of term D is ID, and the average load current of neutral line is Ik. Calculate the three-phase imbalance as

$$\tau = \frac{I_k}{I_B + I_C + I_D} \tag{8}$$

According to the relationship between polar coordinates and complex numbers. The vector Ik value is calculated as

$$I_k = \left(\left(I_B - \frac{1}{2} I_C - \frac{1}{2} I_D \right) + \frac{3}{4} (I_D - I_C)^2 \right)^{\frac{1}{2}} \tag{9}$$

If there is a neutral line in the three-phase load, the main reason for this phenomenon is that the current in the line causes an imbalance, which has little effect on the voltage. In order to simplify the problem, assuming that the average single-phase voltage is equal, the power factor is the same, and the value is 1, the three-phase imbalance is calculated by using Equation (7)-(9)

$$\tau = \frac{\left(\left(P_B + \frac{1}{2} P_C - \frac{1}{2} P_D \right)^2 + \frac{3}{4} (P_D - P_C)^2 \right)^{\frac{1}{2}}}{P_B + P_C + P_D} \tag{10}$$

where τ represents the degree of three-phase imbalance; PB, PC, PD represents the electrical load of phase B, phase C, and phase D.

According to the quantitative relationship between the three-phase load imbalance and the user load of the low-voltage distribution network mentioned above, an imbalance optimization model is constructed. Assuming that the number of users in a low-voltage station area is K, the user load access phase sequence can be described by the matrix

$$X = \begin{bmatrix} X_{B1} & X_{C1} & X_{D1} \\ X_{B2} & X_{C2} & X_{D2} \\ \vdots & \vdots & \vdots \\ X_{BK} & X_{CK} & X_{DK} \end{bmatrix} \tag{11}$$

Let [PB. PC, PD] =PK to solve for the minimum three-phase load imbalance,

$$\tau = \frac{\left(\left(P_B + \frac{1}{2} P_C - \frac{1}{2} P_D \right)^2 + \frac{3}{4} (P_D - P_C)^2 \right)^{\frac{1}{2}}}{P_B + P_C + P_D} \leq \tau_0 \tag{12}$$

where τ0 represents the allowable maximum value of the three-phase load imbalance.

5. Optimization method of three-phase imbalance in distribution network

5.1. Manual adjustment form

Based on manual adjustment of wiring and switches to achieve equal load distribution. Based on the actual operation data in the past as a reference, through the real-time monitoring data of the actual operation on site, the load is evenly distributed by manually adjusting the line and switching, enhance the role of three-phase load distribution. It is recommended to use the three-phase low-voltage short wiring of DZ20 and three ceramic plug-in fuses of RC1A type, respectively, to connect the load side of the three-phase circuit breaker in series in the fuse, and provide power supply based on the three-phase parallel connection. During operation, only one phase is in the working state, and when replacing the power supply, the three-phase switch must be cut off and the fuse plug inserted into the socket of the pre-working phase to restore the circuit breaker to the working state to achieve transposition. This

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method itself is completed by manpower, which has certain unpredictable characteristics of the process, and at the same time cannot realize the real-time tracking of load changes, and cannot achieve the corresponding load adjustment purpose.

5.2. Enhanced reactive power compensation equipment

In terms of power system operation, three-phase imbalance and reactive power itself have inseparable characteristics, on the basis of conventional SVC and SVG reactive power compensation technology, through the existing control methods, to achieve reactive power compensation, suppression of three-phase imbalance and other basic performance. However, this type of equipment is often installed on the low-voltage side of the distribution network transformer to achieve the corresponding centralized compensation effect. Although the power supply quality regulation effect of the transformer outlet can be realized, it cannot achieve the active regulation of the transformer operating status, based on the three-phase load problem of unclear line distribution, it is still impossible to achieve a positive and effective regulation effect, and the low voltage often still exists.

5.3. Load compensation device

With the rapid development of electronic products, the main reactive power compensation devices at present include static synchronous compensator devices and reactive power compensation devices. By studying the switching scheme of capacitors and the compensation principle, the three-phase imbalance problem of distribution network is improved. For example, the optimal control algorithm based on dq transformation is used to control the TCR+FC type reactive power compensator device to quickly steal capacitors to realize the comprehensive compensation of reactive power and three-phase imbalance of the system; some researchers have developed a TCR+TSC type SVC split-phase reactive power compensation device, which adjusts the active current of each phase through experiments to achieve the purpose of optimizing the three-phase imbalance

5.4. Three-phase balance optimizes commutation

The three-phase balance optimization commutation scheme is the most fundamental and direct optimization scheme to improve the three-phase imbalance problem of the distribution network by adjusting the access phase sequence of the power load in the distribution station area. In the early stage, the phase sequence of the incoming load was changed manually, and when wiring, the load was evenly distributed on the three phases of the distribution network as much as possible, and when the three-phase imbalance was serious, the load was consciously adjusted by hand, so that the entire load was in a balanced operating state. With the rapid development of electronic technology, the time-consuming and labor-intensive method of manually adjusting the load phase sequence has gradually been replaced by intelligent commutation switches. First, the intelligent device collects the load data of the distribution transformer and the power terminal, and then judges it through intelligent logic, and adjusts the phase sequence of the power load of part of the distribution network through the load control device, so as to fundamentally and directly improve the three-phase load imbalance problem.

6. Future Trends

The flexible access characteristics of distributed power generation, the uncertainty of output and the time-varying nature of load bring many challenges to the distribution network, and at the same time, in actual operation, the distribution network is mostly three-phase unbalanced, in order to solve the three-phase imbalance problem, the three-phase unbalanced distribution network reconstruction model with the minimum active power and the minimum three-phase imbalance as the objective function. The results show that the three-phase current injection method uses a single-phase node admittance matrix to describe the three-phase network, which fully considers the influence of the volatility of a large number of single-phase distributed power sources and the time-varying nature of single-phase load on the network, so the solution accuracy of the proposed algorithm is higher than that of other algorithms in the active distribution network reconstruction model considering the three-phase imbalance. The large

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M method is used to relax the constraint of the disconnected line, avoid the influence of the constraint of the disconnected line on the model, use the circle inscribed regular 12-sided shape to approximate the circular constraint, linearize the nonlinear constraint, and improve the solution efficiency of the algorithm; at the same time, the dynamic reconstruction of the distribution network alleviates the three-phase imbalance of the distribution network, reduces the active loss of the distribution network, and with the integration of energy storage, the optimization effect of the reconstruction on the distribution network will be further improved.

7. Conclusion

The three-phase imbalance problem of distribution network has brought many impacts to people's production and life, and the current research strategies for alleviating this problem can be mainly summarized into the above three. This article reviews the impact, hazards and use of load compensation devices and three-phase balance optimization commutation to reduce three-phase imbalance. This study does not require investment in new equipment and equipment, and the cost is lower than that of reactive power compensation device, but the most effective way to optimize the three-phase imbalance problem is to establish its functional model, and use intelligent commutation device to greatly improve efficiency and minimize the impact.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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