Analysis and Research of Three-phase Unbalance in Distribution Transformers

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Abstract. The distribution transformer unbalanced operation status will affect the life of the transformer and increase the losses of the transformer besides a series of problems such as grid voltage drop, flicker, low power factor, line losses increase. This article analysis harm caused by the unbalanced operation of distribution transformers from the perspective of power quality and the measures dealing with three-phase unbalanced of distribution transformers.

1. Introduction
The problem of three-phase unbalance on the distribution side becomes increasingly serious, which leads to increasingly serious power quality problem as a result of significant change of structure of the load structure of power distributed and obvious increase of residential electricity and types of electric equipments along with rapid development of national economy. The long-term running with three-phase unbalance of the distribution system shall lead to a series of problems, such as increase of transformer loss, reduction of output of the transformer, reduction of the active output of the motor, increase of loss of the distribution line, damage of electric equipment of the user, etc. There are many measures for handling the three-phase unbalance in the distribution transformer so far, mainly including load transfer, redistribution and phase commutation of the load of the user, reactive compensation, etc.

2. Harm of three-phase unbalance in the distribution transformer

2.1. Increase of transformer loss
The power loss of the distribution transformer includes no-load loss (also called iron loss) and load loss (also called copper loss), wherein the no-load loss is constant basically, and the load loss shall be changed along changes of the load of the transformer and be in direct proportion to the second power of the load current. Moreover, the total loss of three-winding during running with three-phase unbalance in the distribution transformer can be calculated by using following formula:

\[
P_n = (I_a^2 + I_b^2 + I_c^2)R
\]

In the formula, \(I_a\), \(I_b\) and \(I_c\) are the three-phase load currents; R indicates the resistance of the secondary side winding of the transformer. The current of each phase of the winding when the three
phases are unbalanced shall be \((I_A + I_B + I_C)/3\); and the total loss of the three-phase winding should be

\[
P_d = \left[\frac{(I_A + I_B + I_C)}{3}\right] \times R
\]

And the added loss due to three-phase unbalance shall be

\[
\Delta P = \left[\frac{\left(I_A - I_b\right)^2 + \left(I_b - I_c\right)^2 + \left(I_c - I_A\right)^2}{3}\right] \times R
\]  

### 2.2. Harm of three-phase unbalance of output voltage in the distribution transformer to electric equipments

The connecting method of three-phase four-wire system is taken in the low-voltage distribution system generally in China; and the three-phase current on the secondary side of the transformer shall be asymmetric and the zero-sequence current, that is, neutral point displacement shall be generated in the neutral wire when the three-phase load runs asymmetrically, as shown in Figure 1; and \(U_A\), \(U_B\) and \(U_C\) in the Figure 1 are the three-phase symmetrical voltage. The voltage at the center when the three phases run symmetrically shall be \(U_N = 0\); and when the three phases run asymmetrically, \(U_N' \neq 0\) and \(U_B' > U_C' > U_A'\); therefore, the asymmetrical problem shall occur to the phase voltage on the secondary side; the greater the neutral point displacement, the more serious the asymmetrical load phase voltages of all phases caused would be; and some phase voltages may be too high, or even increased to close to the line voltage which may shorten the service life of some household appliances, and even lead to burnout because the load cannot work normally.

![Figure 1: Schematic diagram of neutral point voltage shift](image)

### 2.3. Increase of loss of the distribution line

The current shall be in direct proportion to the second power of the current passing through the line by using the power loss generated by the conductor. The line shall have the minimum power loss when the three-phase current is balanced in presence of symmetric three-phase voltage in the three-phase four-wire power supply circuit. The increased part of the power shall be the added loss \([2]\) of the unbalanced current of the line when the three-phase current is not balanced; while when the three-phase four-wire power supply is available and the three phases are balanced, the active power thereof shall be:

\[
P_{ii} = 3I^2R_i
\]  

The load current of each phase shall be \(I_A\), \(I_B\) and \(I_C\) when the three phases are not balanced, and the average load current shall be
\[ I_{pv} = \left( I_A + I_B + I_C \right) / 3 \]  
\( \text{(5)} \)

Therefore, the three-phase unbalanced degree shall be:
\[ \beta_v = \frac{I_v - I_{pv}}{I_{pv}} \times 100\% \]  
\( \text{(6)} \)

In the formula, \( \beta_v \) indicates the unbalanced degree of each phase; and \( I_v \) indicates the load current of each phase.

The formula of line loss to be applied to three-phase unbalance in Literature [3] shall be:
\[ P_{12} = (I_A^2 + I_B^2 + I_C^2)R_1 + I_N^2R_N \]  
\( \text{(7)} \)

\[ \eta = 2\beta_A^2 + 2\beta_B\beta_n + 2\beta_n^2 + 2 + \frac{4}{3}[(1+\beta_A)(1+\beta_n)\cos\phi_n \]  
\[ + (1+\beta_A)(1-\beta_n-\beta_n)\cos\phi_A + (1+\beta_n)(1-\beta_A-\beta_n)\cos(\phi_n-\phi_A)] \]  
\( \text{(8)} \)

\( \eta \) indicates the increasing rate of loss of the line when the three phases are unbalanced; from the formula, the greater the degree of asymmetry is, the greater the added loss as a result of running and delivery of the power with identical capacity would be.

2.4. Reduction of active output of the induction motor

The unbalanced three-phase voltage as a result of unbalanced three-phase load of the transformer shall include the positive-sequence voltage component, the negative-sequence voltage component and the zero-sequence voltage component. The negative sequence potential shall generate the revolving magnetic field opposite to the positive-sequence potential and having the effect of brake when the motor is powered on. The revolving direction of the motor shall be still consistent with that of the positive-sequence magnetic field because the positive-sequence magnetic field is greater than the negative sequence magnetic field; however, the output power of the motor shall be reduced due to brake effect of the negative sequence magnetic field; and at the same time, the motor may be trapped in vibration as a result of periodic torque pulsation because the positive magnetic field and the negative magnetic field have the periodic effects.

Further, the three-phase unbalance shall also lead to the problems, such as heating of the transformer, reduction of output of the transformer, the serious threat to safety running of the power grid as a result of malfunction of the protective elements of the power grid taking the negative-sequence component as startup, etc.

3. Measures of handling three-phase unbalance

3.1. Phase Balancing, PB

The real-time measurements of current, voltage, power, etc. can be realized by using the intelligent monitoring terminal, for example, the type and the habit of power consumption of the user can be analyzed upon getting the daily load curve of the user, and the unbalanced distribution system can be balanced by using the phase-sequence balance exchange technology.

The phase-sequence balance exchange technology shall refer to the direct method of balancing the load of the distribution network with high efficiency and low cost, and the mathematical model thereof shall be one mixed-integer non linear programming model. The goal of phase balancing (PB) is to homogenize reduction of the voltages of the distribution lines of all phases by reducing loss of the active power and improving distribution of the voltages, and the major mathematical model thereof is
to set up the corresponding mathematical relationship between the degree of unbalance of the loss of the distribution line, the voltage reduction and the phase current at the nodes of all phases, etc. and the phase-sequence index connected with all loads and the distribution network as the objective function and minimize all objective functions after finding the best phase-sequence connection method between the load and the distribution network by using the intelligent optimization method. Moreover, the basic flow chart is as follows:

![Algorithm flowchart of phase balancing.](image)

The phase-sequence exchange strategy of the distribution system in [6] was on the basis of one expert system proposed in the text, in order to preventing the overcurrent relay on the neutral wire from tripping while reducing the current of the neutral wire. The method of solving the phase balance on the basis of immune algorithm was proposed in [11], and the phase current unbalance and the outage cost of the power service of the user were taken into account in terms of the objective function in the text. The new method was proposed in [7], more specifically, introducing the new winding connection into the common double-winding transformer by using the switching operations to balance the phase. The method of finding best phase balance between the distribution transformer and the secondary feeder by using the particle swarm optimization algorithm (BF-PSO) taking bacterial foraging as the guidance was proposed in [8], and the objective function in the text is composed of four parts including the current of the neutral wire, the commutation cost, the reduction of voltage and the line loss. These secondary objective functions were integrated as one multi-object function after
being fuzzification. The particle swarm optimization was also applied to solution of balancing among the phases, but was restricted to the radial distribution system. From the recombination of feeder, the text mentioned to distribute the load on the main feeder uniformly by using the section switches of the feeder in terms of phase-sequence balancing of [10] because 1. The connection between the load of the user and the distribution network could not be switched automatically among the phases; 2. The lasting time curve of the load must be considered on the basis of correct power loss model, rather than to implement operations on one single point on the load curve.

The degree of unbalance of the distribution network can be minimized from the source of the phase-sequence balance of the load maximally; however the complete balance of the three phases cannot be implemented by eliminating the unbalanced current fundamentally due to diversity and randomness of the load. At the same time, the identical phase-sequence balance algorithm and scheme may not be applicable for the structures of the other distribution networks because of specificities of different distribution network. Moreover, the line of the three-phase asynchronous motor cannot be subjected to the phase-sequence exchange, or the motor may be damaged as a result of reverse rotation of the motor, etc. if the three-phase revolving load exists in the distribution network.

3.2. Reactive-power Compensation, RC

The total power of the balanced three-phase system shall be constant and have nothing to do with the time; while the total power of the unbalanced three-phase system shall fluctuate up and down near the potential value; therefore, the balancing device shall be equipped with the electromagnetic element, such as the reactor, the capacitor, etc. for storing the electromagnetic energy temporarily when transforming the unbalanced three-phase system as the balanced three-phase system, in order to form the compensating network of compensating the unbalanced current as the balanced current. The reactive compensating device or the zero-sequence compensator based on the zigzag transformer is used mainly at present; and the degree of unbalance of the three-phase current on the power supply side can be reduced by using the reactive compensation of the compensating device to the unbalanced current. Moreover, the power factor can be improved and the loss can be reduced, and the stability of the system can be increased during running when the reactive compensating device is applied to compensation.

4. Conclusion

The loss of the power grid and the electric equipments of the users could be increased, the fault rate could be increased, the service life could be shortened, the normal running of the equipment might be affected, the correct actions of the relay protection and the automatic devices might be affected, the deviation may occur in measurement, and the communication system might be interfered, etc. as a result of excessive three-phase unbalance. Some relevant literatures for handling the three-phase unbalance of the distribution network were summarized in this text in allusion to the distribution system. Seen from the investment cost, the transfer delivery of load had the minimum cost, and the cost of the compensation equipment; and D-STARCOM and APF were expensive to common distribution network at present; therefore, the use thereof was limited greatly. The cost invested of the phase-sequence balancing technology of load falls in between; however, configuration and selection of nodes of the users, stability and the reliability during running the device should be studied intensively because the detailed information for connection of load is required.

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