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Fast Unbalanced Three-phase Adjustment base on Single-phase Load Switching

Yanwei Zheng*[1], Lisheng Zou[2], Jian He[2], Yongyi Su[2], Zhiquan Feng[1]
[1]Shandong Provincial Key Laboratory of Network based Intelligent Computing, School of Information Science and Engineering, University of Jinan, 106 Jiwei road, 250022, Jinan city, China, telp/fax: +086-531-82765934
[2]Department of Production and Technology, Linyi Power Supply Corp. 130 Jinqueshan road, 276001, Linyi city, China, telp/fax: +086-539-8702219
*Corresponding author, e-mail: ise_zhengyw@ujn.edu.cn

Abstract

To balance three-phase loads in distribution network with abundant of single-phase loads, a new wiring method and three-phase loads adjustment policy was proposed in this paper. In the wiring method, a single-phase load was connected with phase A, B and C of trunk line by a controller. When the load of trunk line was unbalanced, the controller will switch the connected single-phase loads from one phase to another to balance it. The minimum count of loads adjustment algorithm and the most balance adjustment algorithm were proposed, which can adjust the three-phase load of trunk line to roughly balance automatically. This method can solve the serious three-phase unbalance problems of the trunk lines with aboundant of single-phase loads. It may instead of capacitive compensation in low voltage distribution network to improve power quality and reduce network losses.

Keywords*: three-phase unbalance, unbalanced three-phase adjustment, the least load adjustment, the most balance adjustment, distribution network*

1. Introduction

The wiring method of most low-tension transformers was Y/Yn0 and 3-phase/4-wire. There were large numbers of single-phase loads in country distribution and city resident distribution network. The single-phase loads remained randomly change, which might bring 3-phase unbalance unavoidably. There were many other reasons may bring unbalanced 3-phase, such as irrational structure of network, occasional and seasonal using of electricity, malfunction of equipments, et al.[1]. The primary effect consequences of unbalanced 3-phase is wasting of power in transmitting. An academic calculation of theoretical line loss for low-voltage distribution network was given out in [2]. Unbalanced 3-phase might affect power quality problems [3], such as unbalance of 3-phase voltage, overheated to burn the neutral point, et al. In general requirements, the unbalanced 3-phase degree of low voltage of power transformer was no more than 10%, and the degree of low voltage of trunk line was no more than 20%.

The calculating of unbalanced 3-phase ratio was complicated in dynamic systems. In [4] a function was built between sequence capacity and the power of 3-phase unbalanced loads, which predigested the calculating of unbalanced degree as the ratio of negative sequence capacity to the positive sequence capacity of the load. In [5], the calculating methods of unbalanced degree for 3-phase/3-wire and 3-phase/4-wire were analyzed and compared. The precision and application range was also given in [5]. In [6], a new method for unbalanced three-phase power flow calculation in islanding micro grid was proposed, which taked the static P-f and V-Q characteristics of each distributed generation resources (DGRs) into account. To accurately calculate the power flow of distribution network connected with various distributed powers, a 3-phase unbalanced power flow algorithm based on forward and backward substitutions was proposed in [7], which used the laterals delaminating technology to speed up the calculation.

Because the parameters of power network were dynamic, The flow calculation method was difficult to meet real-time requirements. In real-time applications, watching equipments of unbalanced 3-phase were required. An unbalanced 3-phase watching system based on digital

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signal processing (DSP) was given in [8], which might detect the unbalanced 3-phase degree of voltage with high precision. A watching and early-warning system for overload, unbalanced load and unbalanced voltage in distribution network was proposed in [9].

The methods on adjustment of unbalanced 3-phase to banlance now was largely based on compensation. The development of compensation could be divided into three phases: the synchronous compensator, the adjustable parallel capacitor compensation (APCC), and the static var compensator (SVC) [10]. The compensation model of the 3-phase unbalanced system was introduced in [11, 12], where the compensation admittance formula was also derived. The compensation used capacitors as much as possible instead of inductors. An all-capacitor adjusted compensation model based on vector analysis was established in [13], which goal was to make the minimum line loss. An algorithm to minimize the power loss was used in [14], which could make full use of existing capacitors to achieve optimal compensation effect. Two balancing Compensation circuit structures base on single-phase Static Synchronous Compensator (STATCOM) and a voltage-reactive power control method were proposed in [15], which ensured the total harmonic distortion (THD) of output current being less than 5%. The filter in traditional detection methods was abolished to simplify the detection method [16]. The hybrid series compensation method based on single-phase static synchronous series compensator (SSSC) was proposed in [17]. Compared with the method that all three phases employ SSSC, this method was more economical. An unbalanced 3-phase rectifier phase-locked loop based on pulse width modulation (PWM) was designed in [18]. A compensation system adapt to 3-phase/3-wire at the same time to 3-phase/4-wire was designed in [19], which used a fuzzy controller to achieve the capacitor switching switch. Three-phase/level/switch neutral-point clamped VIENNA topology was very suitable for AC-DC unidirectional power rectifier application for its low current harmonics and low blocking voltage stress on the power semiconductors. A novel natural frame control scheme for a VIENNA rectifier under three unbalanced operation conditions was proposed in [20].

These compensation systems were applicable for the adjustment of roughly balanced system. Generally, by good planning, it might be roughly balanced of 3-phase in distribution network. In [21], an urban distribution network planning optimal algorithm was introduced. It researched a new colony intelligence optimization algorithln that called Bacterial Colony Chemotaxis algorithm (BBC) to run the distribution network in a roughly balance. In [22], Hupfeld and Delphi method was used in economic Analysising for distribution power grid planning.

With the combination of 3-phase compensation and single-phase compensation, the range and speed of adjustment was growing. However, in low voltage distribution network, there were a large number of single-phase load, which made more and more extreme imbalance. In this case, making general balance between 3-phase was the basic approach. There were two methods to make it. General way to balance the loads was reactive power compensation [23], but it need large capacity of capacitors and Inductances. Another way was to switch single-phase load from large load phase to small load phase, which was introduced in [24], that was a basic approach for extreme unbalance adjustment.

In this paper, we improved the wiring structure and adjustment algorithm in [24]. The single-phase loads were divided into static loads and variable loads. By switch some variable loads to small load phase from large load phase to make the 3-phase mainline be balance. According the difference of the adjustment methods, we proposed two policy-- the minimum count of loads adjustment policy and the most balanced load adjustment. These two methods were separated suitable for rapid real-time adjustment and restarting adjustment when it was serious imbalance.

2. Wiring Structure

There are large numbers of single-phase load in country distribution and city resident distribution network. Figure 1 shows the power network wiring structure. We suppose the loads of 3-phase are I_{A1}, I_{A2}, …, I_{Am}, I_{B1}, I_{B2}, …, I_{Bn}, I_{C1}, I_{C2}, …, I_{Ct}, where $I_{Ai}(1 \le i \le m)$ are the single-phase loads which connected to phase A, $I_{Bj}(1 \le j \le n)$ are connected to phase B, and $I_{Ck}(1 \le k \le t)$ are connected to phase C. These single-phase loads are generally balanced in designing time, which is presented in (1).

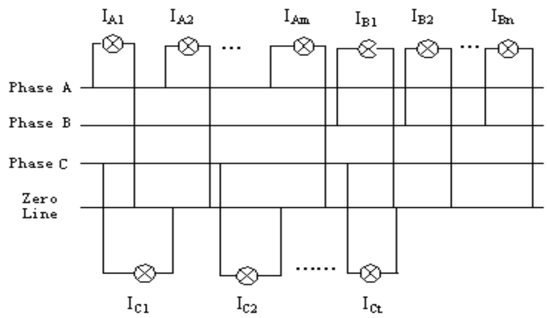


Figure 1. Wiring Structure of Single-load

$$\sum_{i=1}^{m} I_{Ai} \approx \sum_{i=1}^{n} I_{Bi} \approx \sum_{i=1}^{t} I_{ci} \qquad (1)$$

All loads run at rated load or full load at any time is impossible, so (1) does not hold. We need to redistribute loads to make (1) hold. In Figure 1, we could not switch a load from one phase to another. We need to modify the wiring structure to switch loads, which is shown in Figure 2.

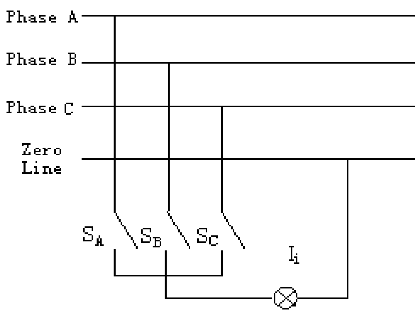


Figure 2. Wiring Structure Support Adjusting Loads between Phases

In Figure 2, some loads I_i is connected with the 3-phase lines through a contactor. If contactor S_A is closed, load I_i is supplied by phase A. If contactor S_B or S_C is closed, load I_i is supplied by phase B or C. Then a single-phase load I_i may easily switch to any phase of A, B, or C. Only one or no one of S_A, S_B and S_C could be closed at any time, which can be expressed as (2).

$$S_i = A_i\overline{B_i}\,\overline{C_i} + \overline{A_i}B_i\overline{C_i} + \overline{A_i}\,\overline{B_i}C_i + \overline{A_i}\,\overline{B_i}\,\overline{C_i} \qquad (2)$$

With different of wiring structure from [24], all single-phase loads are divided into static loads and variable loads. If a load is large or stable, it will be considered as a static load. The static load will be fixedly connected to phase A, B or C, which means that the static load can't switch from one phase to another. The ***static*** means that the wiring method is static, but the load value will be variety in running time. If a load is not large or stable, it will be considered as a variable load. The variable loads will connected with trunk line as shown in Figure 2, which means that the variable load can switch from one phase to another. The static and variable loads all equiped watching equipments to monitor the current load, which is the basis of adjustment.

The division of the contactor S_A, S_B and S_C is controlled by the relay of the controller. The division of relay is controlled by a single-chip processor. The single-chip processor is controlled by a computer remotely through GPRS.

3. Adjustment Policy

When the 3-phase unbalanced in running time, the computer system can recommend the load need to adjust. There are two method to adjust it. One way is to adjust as little count of loads as possible, another way is to adjust to the most balanced status. The former is called the minimum count of loads adjustment algorithm (MCLA), the latter is called the most balance adjustment algorithm (MBA).

3.1. The Minimum Count of Loads Adjustment Algorithm

Three-phase unbalanced threshold is set to σ. When the 3-phase unbalanced ratio is greater than σ, we need to switch the single-phase load to make the 3-phase unbalanced ratio less than or equal to σ. Because the static loads can't be switched, we suppose the static trunk line loads of phase A, B and C are L_{AS}, L_{BS} and L_{CS}, which current value are I_{AS}, I_{BS} and I_{CS}.

We suppose the variable loads congregation of phase A is $L_{AV} = \{L_{A1}, L_{A2}, ..., L_{Am}\}$, congregation of phase B is $L_{BV}=\{L_{B1}, L_{B2}, \ldots, L_{Bn}\}$, and congregation of phase C is $L_{CV}=\{L_{C1}, L_{C2}, \ldots, L_{Ct}\}$. The current value of L_{Ai}, L_{Bj} and L_{Ck} are I_{Ai}, I_{Bj} and I_{Ck}. The adjustment policy is shown as following:

(i) Calculating the total variable loads of every phase of the trunk line according (3).

$$I_{AV} = \sum_{i=1}^{m} I_{Ai}, I_{BV} = \sum_{i=1}^{n} I_{Bi}, I_{CV} = \sum_{i=1}^{t} I_{Ci} \quad (3)$$

(ii) Calculating the total loads of every phase of the trunk line according (4).

$$I_A = I_{AS} + I_{AV}, I_B = I_{BS} + I_{BV}, I_C = I_{CS} + I_{CV} \quad (4)$$

(iii) Calculating the average load according (5).

$$I_{avg} = \frac{I_A + I_B + I_C}{3} \quad (5)$$

(iv) Calculating the 3-phase unbalanced ratio according (6). If β>=σ, it turns to step (v). If β<σ, it is finished of the adjustment.

$$\beta = \frac{I_M - I_N}{I_{avg}} \times 100\% \quad (6)$$

(v) Calculating the maximal phase M and the minimal phase N according (7) and (8).

$$M = \{X \mid I_X = Max\{I_A, I_B, I_C\}, X \in \{A, B, C\}\} \quad (7)$$

$$N = \{Y \mid I_Y = Min\{I_A, I_B, I_C\}, Y \in \{A, B, C\}\} \quad (8)$$

(vi) Searching the load i in L_M which is satisfied (9).

$$i = \{X \mid |I_M - I_N - 2I_{MX}| \le |I_M - I_N - 2I_{MY}|, X \ne Y, 1 \le X, Y \le p\} \quad (9)$$

Where p is the count of loads of L_M.

(vii) Switch the load L_{Mi} of L_M to L_N.

$$L_M = L_M - \{L_{Mi}\}, L_N = L_N \cup \{L_{Mi}\} \quad (10)$$

(viii) Turning to step (i) to continue adjust.

3.2. The Most Balance Adjustment Algorithm

The pre-condition of this algorithm is same with the MCLA algorithm.

(i) Setting all variable loads into congregation L_V according (11), then setting L_{AV}, L_{BV} and L_{CV} be empty congregation.

$$L_V = L_{AV} \cup L_{BV} \cup L_{CV} \tag{11}$$

(ii) If L_V is empty, the algorithm is finished. If L_V is not empty, it turns to (iii).
(iii) Calculating the total variable loads and the total loads according (3) and (4).
(iv) Searching the maximal load L_i from L_V according (12).

$$i = \{x \mid L_x \le L_y, x \ne y, L_x \in L_V, L_y \in L_V\} \tag{12}$$

(v) Searching the minimal load of phase N according (8).
(vi) Shifting L_i into L_N from L_V according (13) and (14).

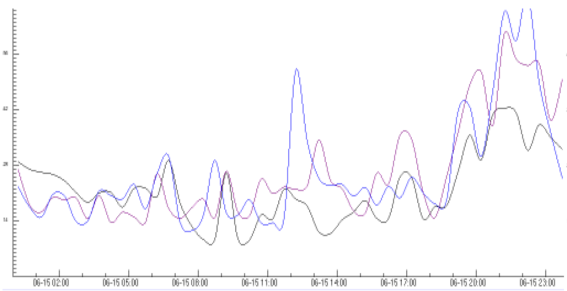
$$L_N = L_N \cup \{L_i\} \tag{13}$$

$$L_V = L_V - \{L_i\} \tag{14}$$

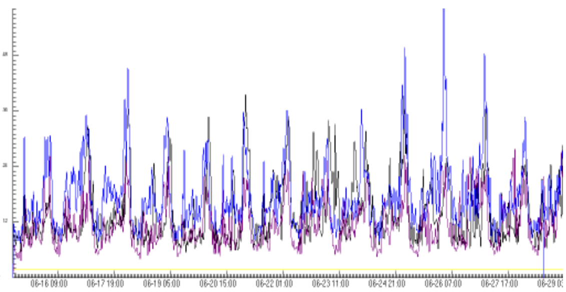
(vii) Turnning to step (ii) to continue.

4. Results and Analysis

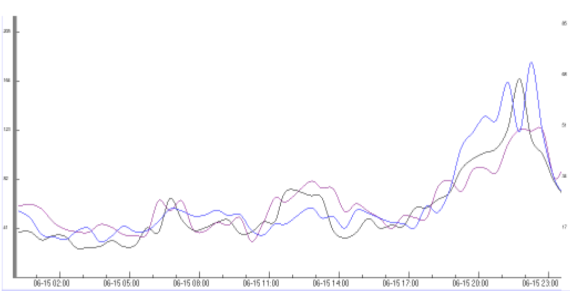
The load curve between 2011/6/15 00:00 and 24:00 is shown in Figure 3, where the horizontal axis is time, and vertical axis is the load. The load of a phase is shown in black, while B phase is red and C is blue. The load curve of Zhangzhuang public transformer is shown in (a). It can be seen from the figure, the transformer load is roughly balanced in most of the time. However, in the peak period of 12:00 and 22:00, the C-phase and B-phase load growth more than A-phase, which results high rates of unbalanced 3-phase. Figure 3 (b)-(d) are other 3 curves of transformer, they are similar to (a).



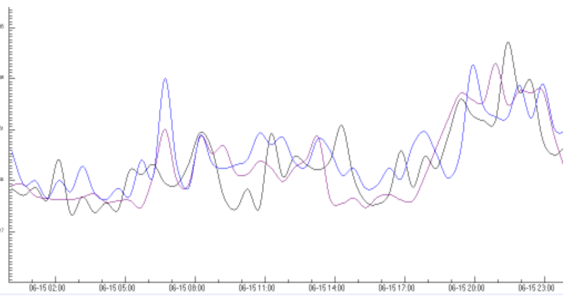
(a) Zhangzhuang public transformer



(b) Yanwuju private transformer



(c) Qianyuan private transformer



(d) Houweitun public transformer

Figure 3. The Load Curve of Distribution Network Transformer

The average load, the average unbalanced rate, the maximum unbalanced rate and the minimum unbalanced rate from Jun. 15, 2011 to Jun. 28 are shown in Table 1. It can be seen from the table, the average unbalanced 3-phase ratio far exceeds the specified value, while the maximum value even close to 300%. The results from Jun. 29 to Jul. 14 are shown in Table 2, when the 3-phase load regulators were enabled. The threshold of 3-phase unbalanced ratio is 0.2. There are no statistics of the maximum and minimum unbalanced rate in Table 2, because the unbalanced 3-phase will be adjusted when the ratio exceeds the threshold.

Table 1. The Statistics of Loads before the Regulators were Installed

Transformer	A-phase(A)	B-phase(A)	C-phase(A)	Unbalanced 3-phase ratio		
				Average	Maximum	Minimum
Zhangzhuang	31.2004	28.2377	29.2843	0.1002	2.9418	0.0160
#2 of Xiaolinzhuang	58.3664	29.6710	51.7468	0.6159	2.9806	0.1479
#1 of Xiaolinzhuang	132.8585	100.4108	102.4076	0.2900	2.8958	0.0058
Houweitun	26.4895	34.3367	32.7778	0.2515	1.4792	0.0053
#2 of Houweitun	42.1246	42.8184	45.2989	0.0731	1.2306	0.0215
#2 of Houqin	52.5395	60.5474	87.0050	0.5167	2.9766	0.0154
Area C of Qianyuan	71.6670	81.2585	72.4619	0.1277	0.8045	0.0145
South of Sanhetun	57.6480	55.4874	56.5165	0.0382	0.9941	0.0287
Office of salt	14.0873	11.6672	17.4592	0.4021	1.6753	0.0344
Hostel of Sanjian	0.3763	24.2894	21.1323	1.5664	2.1785	1.3023

Table 2. The Statistics of Loads after the Regulators were Installed

Transformer	A-phase(A)	B-phase(A)	C-phase(A)	Unbalanced 3-phase ratio
Zhangzhuang	30.3247	32.3325	29.282	0.0995
#2 of Xiaolinzhuang	48.4664	50.8753	48.9832	0.0487
#1 of Xiaolinzhuang	112.6504	115.3563	107.4423	0.0708
Houweitun	34.3506	31.4202	32.5547	0.0894
#2 of Houweitun	44.3102	42.9265	43.2567	0.0318
#2 of Houqin	70.4651	63.2502	63.3158	0.1099
Area C of Qianyuan	76.7724	75.3822	71.6489	0.0687
South of Sanhetun	56.5443	59.3087	56.8895	0.0480
Office of salt	14.2563	15.1007	14.3027	0.0580
Hostel of Sanjian	16.3209	14.2477	14.5538	0.1378

It can be seen from Table 2, most of the unbalanced 3-phase ratio can be adjusted to below 10%. Some single-phase load which cannot be precisely adjusted can also be adjusted to below the threshold.

The effect of the most balance adjustment algorithm is to re-adjust all single-phase loads. Table 3 shows the result. Before using the MBA algorithm, the unbalanced count per day will growth daily until being stability at a high count. This shows that it will be unbalanced quickly after adjustment. If we use the MBA algorithm to adjust the single-phase loads, the unbalanced count will be low in the next day. So the MBA algorithm is suitable to use when unbalanced frequently.

Table 3. The Unbalanced Count per Day before and after using MBA Algorithm

Transformer	Before	After
Zhangzhuang	12	2
#2 of Xiaolinzhuang	15	2
#1 of Xiaolinzhuang	8	0
Houweitun	8	1
#2 of Houweitun	6	1
#2 of Houqin	9	3
Area C of Qianyuan	11	2
South of Sanhetun	6	0
Office of salt	11	2
Hostel of Sanjian	13	3

5. Conclusion

The aim of this paper is the fast 3-phase load adjustment for distribution network with large amount of single-loads. The idea of 3-load adjustment and controller model are proposed in this paper, which changed the wiring structure of single-phase load. Some single-phase loads are connected to all three phase of trunk line by a controller. The controller device can detect the 3-phase load at real-time. When the 3-phase unbalanced ratio exceeds the threshold, it can switch appropriate single-phase loads from a phase to another, thus the 3-phase unbalanced ratio will be adjusted to legal value.

The results show that the MCLA algorithm can adjust the 3-phase unbalanced ratio to roughly balance, and the MBA algorithm is suitable to use when 3-phase unbalanced is serious. This two algorithm can effectively improve the power quality and reduce the network losses.

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