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# A novel method for simultaneous phase balancing and mitigation of neutral current harmonics in secondary distribution systems

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ABSTRACT

In this paper, a novel method is proposed to reduce phase unbalance and mitigate neutral line current harmonics in the secondary distribution systems without using any active or passive shunt device, shunt compensation scheme or phase swapping technique. The proposed strategy employs a Phase Balancer (PB), which has been derived from the conventional three-phase transformer. In order to understand the working of the proposed PB, its analytical treatment is presented using symmetrical components. The application of the proposed PB has also been investigated for different balanced and unbalanced non-linear actual loading cases and the application results are presented.



## 1. Introduction

In the recent years, the concept of smart distribution is taking shape. The emphasis of smart distribution system is on the efficiency enhancement by reducing distribution power losses, improving reliability, maximizing asset utilization and better power quality free from harmonics besides complete automation and integration of distributed energy resources [1]. Therefore, modern distribution systems are gaining significant attention over several power quality issues such as poor voltage regulation, high reactive power, harmonics current burden, phase unbalancing, excessive neutral line current, etc. [2]. By and large the source of these issues is secondary distribution system which is directly connected to the customers. The secondary distribution is typically three-phase four-wire distribution system adopted to supply mixed loading, but it results in serious phase unbalance due to unequal distribution of single-phase loads [3]. The presence of increasing number of non-linear loads such as adjustable speed drives, uninterruptible power supplies, etc. also causes significant neutral current in the three-phase four-wire distribution system as triplen harmonics in phase currents do not cancel each other even under balanced condition and are added up in the neutral line [4]. Therefore, the total neutral line current is contributed by the zero-sequence fundamental and harmonic components of the unbalanced load currents and thus results in the overload of neutral conductor of the three-phase four-wire distribution system [3]. The exponential growth in the non-linear loads is responsible for further worsening of this situation. A study reveals that 22.6% of the distribution sites have a neutral line current in excess of 100% [5]. The phase unbalance increases line losses, deteriorates system voltage profiles, overloads system phases, results in malfunctioning of protective relays, causes saturation problem in the distribution power transformers, increases communication interference, deteriorates power quality, system security and reliability of the electric supply, etc. [4]. The phase unbalance and heavy neutral current are the issues of serious concerns as they deteriorate the overall performance of distribution systems.

A lot of research effort has been carried in the area of phase balancing and harmonic reduction. These research efforts have led to the development of various approaches/methods to deal with the problems of phase balancing and harmonic reduction such as passive filter approaches, active power filter approaches, zig-zag transformer methods and phase swapping techniques. The passive filter approaches [7,8], have been used to reduce the neutral line current. But, passive filters with fixed compensation characteristics are ineffective to filter the current harmonics [9]. Moreover, these methods have a hidden risk of series or parallel resonance [3]. On the other hand, the active power filter approaches [10–20] overcome the drawbacks of passive filters by using the switching mode power converter to eliminate the harmonic currents [9]. However, the construction cost of active power filters in a practical industry is too high and the power rating of the power converters in active power filters is very large [6,9]. This seriously limits the application of active power filters in the power distribution systems. In

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addition, the active power filter schemes are complicated in control [4]. Hybrid filters [9,21–27] can reduce the cost of active power filters but are complex in design.

Zig-zag transformers [3–6,28–30] have been successfully applied to suppress the neutral currents from the supply side. A passive zig-zag transformer is connected in parallel to the load and is designed to have low zero-sequence impedance, allowing the zero-sequence neutral line currents to circulate from the neutral line back to the load. However, passive zig-zag transformers do not suppress the harmonic presents in neutral current due to linear and non-linear loads. Some researchers [3–6,30] have combined the zig-zag transformer with active power filters or single-phase inverter to solve the problem of fundamental and harmonic neutral currents. However, this involves a complex control circuits.

Many researchers proposed phase swapping techniques to reduce the phase unbalance. The phase swapping is a direct and effective way to balance a feeder in terms of phases. In these techniques, the phases of three-phase supply are frequently disconnected and reconnected in different fashion to balance out line unbalance, substation unbalance or load unbalance. Different phase swapping techniques have been proposed in the literature [31–40] which are based on heuristic approaches [31–33], Dynamic Programming [34,35], Mixed-integer Programming [36], Simulated Annealing [37], Genetic Algorithm [38], Immune Algorithm [39], Expert Systems [40] etc. The phase swapping techniques have the potential to ease out phase unbalance to some extent but involve frequent switching due the stochastic nature of the load characteristics and thus makes phase swapping tedious, costly and time consuming for system engineers [39]. Moreover, frequent switching is not desirable due to the cost of switching and other issues related to interruption of supply. Furthermore, the phase swapping does not ease the problem of harmonic currents in the neutral conductor under balanced or unbalanced non-linear loading conditions. A method of phase balancing has been proposed by the same authors to reduce phase unbalance with the help of a novel Phase Balancer [41]. The proposed strategy does not employ any active/passive shunt device, shunt compensation scheme or phase swapping technique, as being employed in earlier established works. However, the analysis of proposed PB [41] is limited to linear loads only. This method needs further analysis and investigation to see the applicability of the proposed PB under non-linear unbalance loads and to explore the behavior of proposed PB in harmonic reduction on the utility side.

Therefore, this paper presents an extension of the basic work done in [41] by the same authors. The analysis of the proposed PB has been carried out to see the behavior of the PB under non-linear unbalanced loading conditions using symmetrical components. Analysis has been also carried out to see the transformation of neutral current harmonics on the utility side. The effect of three phase loads with different power factors on the PB has also been investigated. The proposed strategy employs the same PB to reduce the phase unbalance of the fundamental and harmonic components present in the three-phase unbalanced load currents and as a result reduces the neutral line current magnitude. The effectiveness of the proposed PB is also established under different loading conditions using symmetrical components. Finally, the performance of the PB has been investigated under actual unbalanced non-linear loading conditions. The application results of the PB are presented. The application verifies the theoretical analysis of the proposed PB.

## 2. Symmetrical components analysis

The three sets of *symmetrical components* [42] are designated by the additional sub-script 1 for the positive-sequence components, 2 for negative-sequence components and 0 for the zero-sequence components. The line currents $\boldsymbol{I}_a$, $\boldsymbol{I}_b$, $\boldsymbol{I}_c$ of an unbalanced load can be expressed in terms of symmetrical components $\boldsymbol{I}_{a0}$, $\boldsymbol{I}_{a1}$, $\boldsymbol{I}_{a2}$ by the set of equations:

$$\begin{bmatrix} \boldsymbol{I}_a \\ \boldsymbol{I}_b \\ \boldsymbol{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \boldsymbol{a}^2 & \boldsymbol{a} \\ 1 & \boldsymbol{a} & \boldsymbol{a}^2 \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_{a0} \\ \boldsymbol{I}_{a1} \\ \boldsymbol{I}_{a2} \end{bmatrix} \tag{1}$$

where $\boldsymbol{a}$ is an operator and is given by

$$\boldsymbol{a} = 1\angle 120^\circ \tag{2}$$

Conversely, the sequence components of the line currents can be obtained using (1) and are given by the set of equations

$$\begin{bmatrix} \boldsymbol{I}_{a0} \\ \boldsymbol{I}_{a1} \\ \boldsymbol{I}_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \boldsymbol{a} & \boldsymbol{a^2} \\ 1 & \boldsymbol{a^2} & \boldsymbol{a} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_a \\ \boldsymbol{I}_b \\ \boldsymbol{I}_c \end{bmatrix} \tag{3}$$

Thus the neutral line current with unbalanced load is

$$\boldsymbol{I}_n = \boldsymbol{I}_a + \boldsymbol{I}_b + \boldsymbol{I}_c = 3\boldsymbol{I}_{a0} \tag{4}$$

### 2.1. Harmonic analysis of neutral line current for balanced non-linear load

The non-linearity in distribution system loads causes flow of odd harmonic currents in the supply lines [4]. However, some harmonic currents find their path through the neutral line and thus make the system unbalanced even when the system load is balanced. Let, the $q$th harmonic line current for the phase-A is given by

$$\boldsymbol{I}_a^q = \boldsymbol{I}_a^q \sin(q\omega t + \Phi_q); q = 2m - 1; m \in \{1, 2, 3, \ldots\} \tag{5}$$

When the three-phase load is balanced, i.e., when $\boldsymbol{I_a^q} = \boldsymbol{I_b^q} = \boldsymbol{I_c^q}$, the three-phase line currents for the balanced non-linear load can be expressed as [4]:

$$\boldsymbol{I}_a = I_a^1 \sin(\omega t + \Phi_1) + I_a^3 \sin(3\omega t + \Phi_3) + I_a^5 \sin(5\omega t + \Phi_5) + \ldots \tag{6}$$

$$\boldsymbol{I}_b = I_a^1 \sin(\omega t - 120^\circ + \Phi_1) + I_a^3 \sin(3(\omega t - 120^\circ) + \Phi_3) + I_a^5 \sin(5(\omega t - 120^\circ) + \Phi_5) + \ldots \tag{7}$$

$$\boldsymbol{I}_c = I_a^1 \sin(\omega t - 240^\circ + \Phi_1) + I_a^3 \sin(3(\omega t - 240^\circ) + \Phi_3) + I_a^5 \sin(5(\omega t - 240^\circ) + \Phi_5) + \ldots \tag{8}$$

After simplifying Eqs. (6)–(8), the line currents can be expressed as

$$\begin{bmatrix} \boldsymbol{I}_a \\ \boldsymbol{I}_b \\ \boldsymbol{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & \ldots \\ \boldsymbol{a}^2 & 1 & \boldsymbol{a} & \ldots \\ \boldsymbol{a} & 1 & \boldsymbol{a}^2 & \ldots \end{bmatrix} \times \begin{bmatrix} \boldsymbol{I}_a^1 \\ \boldsymbol{I}_a^3 \\ \boldsymbol{I}_a^5 \\ \vdots \end{bmatrix} \tag{9}$$

Thus,

$$\boldsymbol{I}_{a0} = (\boldsymbol{I}_a^3 + \boldsymbol{I}_a^9 + \boldsymbol{I}_a^{15} + \ldots) \tag{10}$$

$$\boldsymbol{I}_{a1} = (\boldsymbol{I}_a^1 + \boldsymbol{I}_a^7 + \boldsymbol{I}_a^{13} + \ldots) \tag{11}$$

$$\boldsymbol{I}_{a2} = (\boldsymbol{I}_a^5 + \boldsymbol{I}_a^{11} + \boldsymbol{I}_a^{17} + \ldots) \tag{12}$$

It is evident from the Eqs. (10)–(12) that in case of balanced non-linear load, the zero-sequence component is contributed by triplen harmonics, i.e., 3rd, 9th, 15th, … harmonics. The neutral line current for the non-linear balanced load can be obtained using (4) and (10) as

$$\boldsymbol{I}_n = 3(\boldsymbol{I}_a^3 + \boldsymbol{I}_a^9 + \boldsymbol{I}_a^{15} + \ldots) \tag{13}$$