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ISSN: 0193-4120 Page No. 2124 - 2128

# The Symmetrical ZigZag Transformer for Harmonic Currents Reduction in Distribution Load Systems

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***Article Info***
***Volume 83***
***Page Number: 2124 - 2128***
***Publication Issue:***
***May - June 2020***

***Article History***
***Article Received**: 11August 2019*
***Revised**: 18November 2019*
***Accepted**: 23January 2020*
***Publication**: 10 May2020*

**Abstract:**

Non-linear loads in a three-phase three-wire system can cause distortion of line current and voltage waveform due to harmonic currents. The analysis on harmonic currents shows that the dominant are 5th and 7th orders. In increasing of harmonic currents in the power system will affect the power system performance. An investigations on using symmetrical zigzag transformer technique to minimize harmonic currents 5th and 7th order are proposed. This technique is used in a three-phase three-wire system where it is mainly contaminated by negative sequence harmonics (e.g. 5th order) and positive sequence harmonics (e.g. 7th order) to be minimized. The mechanism for minimizing the 5th and 7th order of harmonic currents in the electrical power distribution system is presented in this paper. An experimental results are presented to validate the proposed approach.

***Keywords:** harmonic, nonlinear load, power distribution system, transformer and three phase three wires*

## I. Introduction

The increasing use of nonlinear device and solid state devices has resulted many harmonic currents being injected into the power system [1]. All of these devices are harmonic sources. Ideally, the voltage and current waveforms are perfect sinusoidal. However, due to the increased use of nonlinear devices, the waveform is easily distorted.

In general, harmonics in three phases of three wires are dominated by the 5th and 7th harmonic orders, where the magnitude of the harmonic current is reciprocal by the harmonic sequence [2]. Based on the symmetrical components, the 5th and 7th are negative and positive harmonic sequence respectively. Therefore, the corresponding harmonic sequences can be represented by positive, negative and zero equals 3h + 1, 3h-1 and triplen, respectively, shown in Table 1 [3].

TABLE 1. HARMONIC PHASE SEQUENCE PATTERN IN A BALANCE THREE PHASE POWER SYSTEM

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Harmonic Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | . |
| Harmonic Sequence | + | - | 0 | + | - | 0 | + | . |

Hence, the harmonic equivalent as:

Positive sequence = 3h+1
Negative sequence = 3h-1
Zero sequence = triplen harmonic

Impact from this phenomenon can be caused the equipment heating, equipment malfunction, equipment failure, communication interferences, fuse and breaker disoperation, conductor heating and etc. [4]. In past years, various methods to minimize harmonic current in electric power distribution system have been presented such as LC passive filter [5] and active power filter [6]. However, the LC passive filter contributes a very large and heavy size to reduce the harmonic currents.

Meanwhile, the active power filter uses an inverter with PWM control to inject current to line current of power distribution system to reduce the harmonic currents [7][8][9][10][11]. In addition to that, the active power filter is capable of injecting higher order harmonic currents are compared with passive LC filter. It means that the suppression of the highest harmonic current can be performed better by the

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active power filter. Therefore, active power filter, requires an additional complex circuits, power converters and costly.

Others method to reduce harmonic currents using three phase diode rectifiers with low rating kVA transformers has been proposed.

## II. Harmonic Minimization Method

In this paper, the symmetrical zigzag transformers with low kVA rating to minimize for 5th and 7th order harmonic currents are proposed [12][13][14]. This configuration is shown in Figure 1.

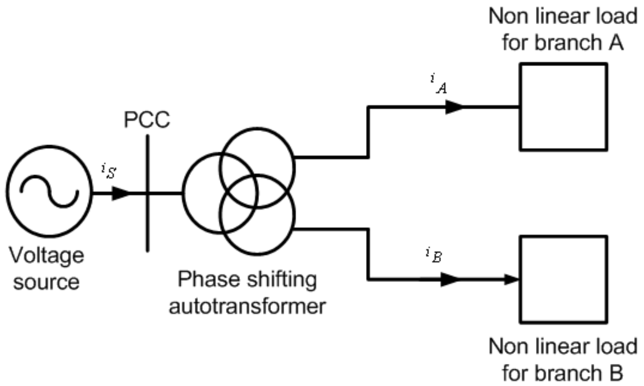



Fig. 1. The distribution system method

Both non-linear loads at branches A and B are connected to symmetric zigzag transformer output voltage. This output voltage is shifted to + 15 ° and -15 °. Mathematically, this output voltage can be represented by V l-lbb + 15 ° and V l-lbb -15 °. Therefore, the current output at load A and B can be expressed by the following equation:

$$i_A(t)=\sqrt{2}I_{1A}\sin\,(\omega t+15^0)+\sum_{h=(6n\pm1)}^{\infty}\sqrt{2}I_{hA}\sin\,(h_A wt+15^0-\alpha_{hA}) \quad (1)$$

$$i_B(t)=\sqrt{2}I_{1B}\sin\,(\omega t-15^0)+\sum_{h=(6n\pm1)}^{\infty}\sqrt{2}I_{hB}\sin\,(h_B wt-15^0-\alpha_{hB}) \quad (2)$$

Hence, the total line current system is:

$$i_S(t)=i_A(t)+i_B(t) \quad (3)$$

Assume the magnitude for load A and B is similar and $\alpha_{hA}=\alpha_{hB}$, therefore:

$$i_S(t)=\sqrt{2}\,[\,I_{S1}\sin\,(wt)+I_{S11}\sin\,(11\,wt)+I_{s13}\sin\,(13\,wt)+......\,]$$

(4)

Equation (4) shows the current flow consists of the 5th and 7th harmonic currents. This means that they have two different directions and will result in cancellation of each other in the symmetry of the zigzag transformer.

### A. Phase Sequence of Harmonics

For a balanced three-phase system, the sequence of voltage harmonic h-th order for each phase can be expressed as follows [13]:

$$V_{ah}(t)=\sqrt{2}V_h\sin\,(h\omega_0 t+\theta_h) \quad (5)$$

$$V_{bh}(t)=\sqrt{2}V_h\sin\,(h\omega_0 t-2h\pi/3+\theta_h) \quad (6)$$

$$V_{ch}(t)=\sqrt{2}V_h\sin\,(h\omega_0 t+2h\pi/3+\theta_h) \quad (7)$$

From the above equation shows that the pattern of phase sequence harmonics in balanced three-phase system is similar in Table 1. However, the parameter of non-distortion waveforms can be written in (8). This equation is referred as a Total Harmonics Distortion (THD).

$$THD=\frac{\left[\sum_{h=2}^{N}(I_h)^2\right]^{1/2}}{I_1} \quad (8)$$

### B. Symmetrical ZigZag Transformer

Figures 2 and 3 show the phases shifting of symmetric zigzag transformers and phasor diagrams, respectively.

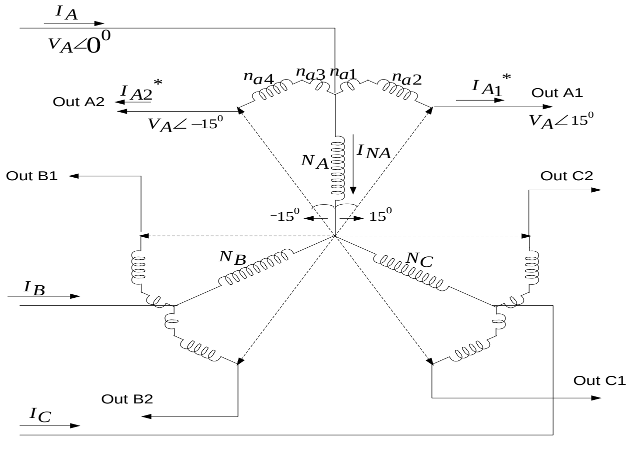



Fig. 2. The phase shifting symmetrical zigzag transformer configuration

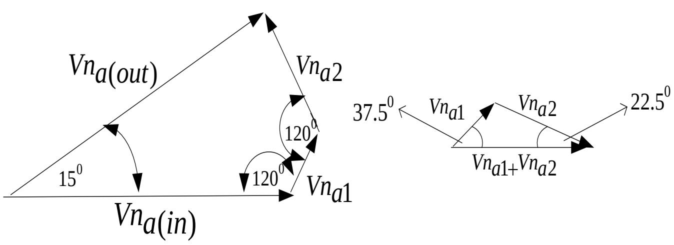



Fig. 3. The phasor diagram for one phase of transformer

The advantages of symmetrical zigzag transformer can produce a phase shifted output voltage at low kVA rated compared with conventional transformers. The formulae to calculate kVA rating can be expressed in (9).

$$Rating\ kVA = \Sigma\, i_{rms}.v_{rms} \qquad (9)$$

Where:

$V_{rms}$ = sinusoidal rms voltage
$I_{rms}$ = sinusoidal winding rms current

Hence,

$$Vn_{a(in)} = \frac{V_{(l-l)}}{\sqrt{3}} \qquad (10)$$

$$Vn_{a1} + Vn_{a2} = 0.15V_{(l-l)} \qquad (11)$$

Therefore, the rating of symmetrical zigzag transformer kVA as shown in (12)

$$kVA = 3\,[\frac{V_{(l-l)}}{\sqrt{3}} * 0.05I] + 6\,[0.069V_{(l-l)} * I/2] + 6\,[0.1V_{(l-l)} * I\ /2]$$

$$kVA = 0.346p.u \qquad (12)$$

## III. RESULTS AND DISCUSSIONS

The experimental work was carried out with an unbalanced load of 0% to 100%. The results show that THDi is varied from 11.2% to 27.9% as shown in Figure 4.

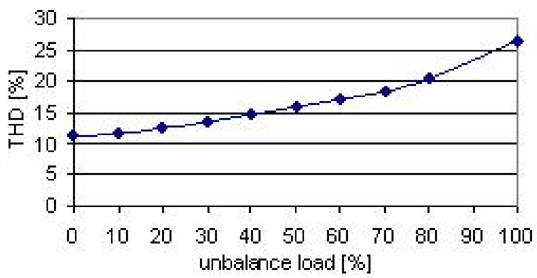



Fig. 4. The effect of unbalanced load to THDi

The comparison of results between before and after reduction of symmetrical zigzag transformer output and Point of Coupling Common (PCC) during system under balanced load are tabulated in Tables 2 and 3.

TABLE 2. MEASUREMENT BEFORE MINIMIZATION

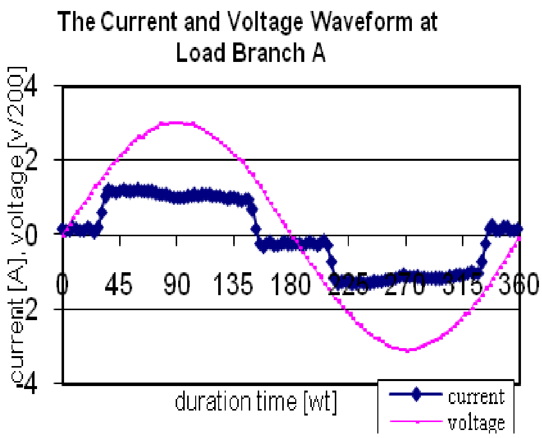
| **Description** | **Before minimization** | | |
|---|---|---|---|
| | **Load of branch A** | **Load of branch B** | **Line current (PCC)** |
| Frequency (Hz) | 50 | 50 | 50 |
| Active power (W) | 350 | 390 | 730 |
| Power factor | 0.74 | 0.88 | 0.86 |
| Voltage (Volt) | 418 | 418.6 | 419 |
| Current (Amp) | 1.0 | 1.0 | 2.0 |
| THD current (%) | 27.8 | 27.4 | 27.9 |

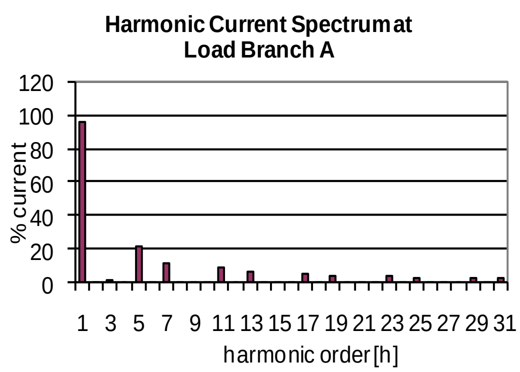
TABLE 3. MEASUREMENT AFTER MINIMIZATION

| **Description** | **After minimization** | | |
|---|---|---|---|
| | **Load of branch A** | **Load of branch B** | **Line current (PCC)** |
| Frequency (Hz) | 50 | 50 | 50 |
| Active power (W) | 340 | 390 | 730 |
| Power factor | 0.74 | 0.87 | 0.87 |
| Voltage (Volt) | 418.5 | 418.2 | 416.5 |
| Current (Amp) | 1.0 | 1.0 | 2.0 |
| THD current (%) | 27.4 | 27.5 | 11.2 |

Tables 2 and 3 show the results THDi reduction between before and after is 27.9% and 11.2%, respectively. This indicate that the THDi is decreased by 16.7%.

Figures 5 and 6 shows the comparison of results between before and after minimization for current spectrum and voltage waveforms.



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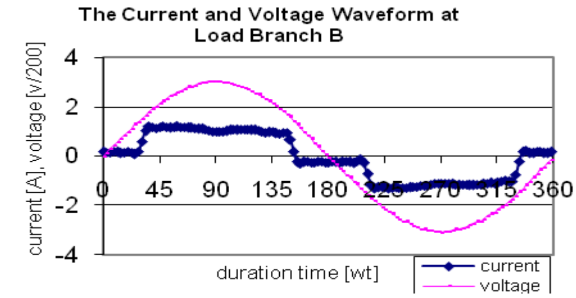


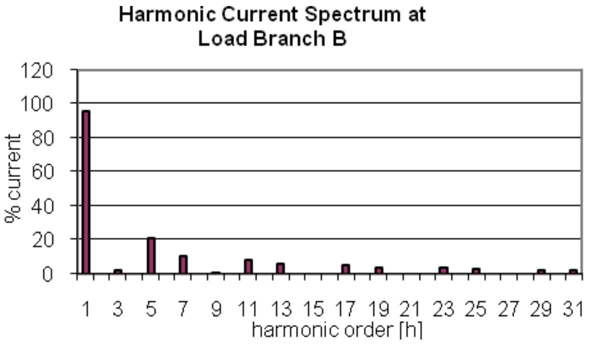
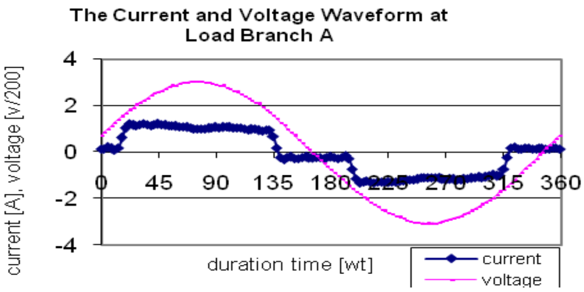
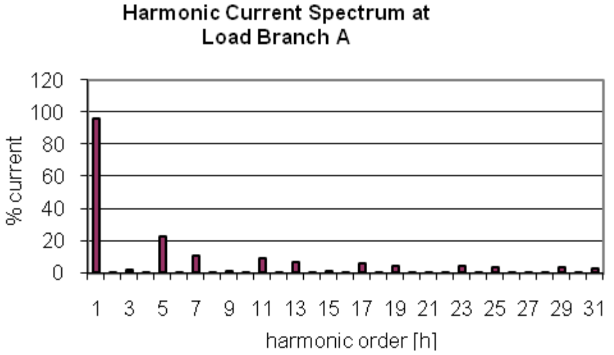
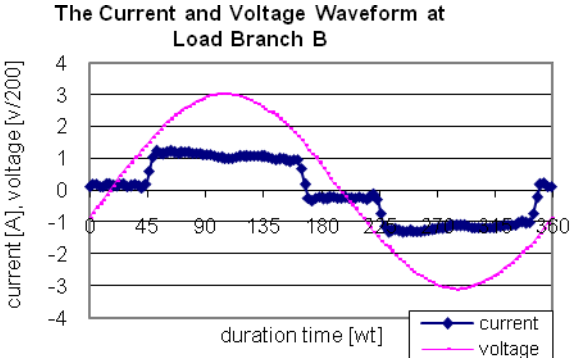




Fig. 5. The current and voltage waveforms and harmonic currents spectrum at load branch A and B before minimization



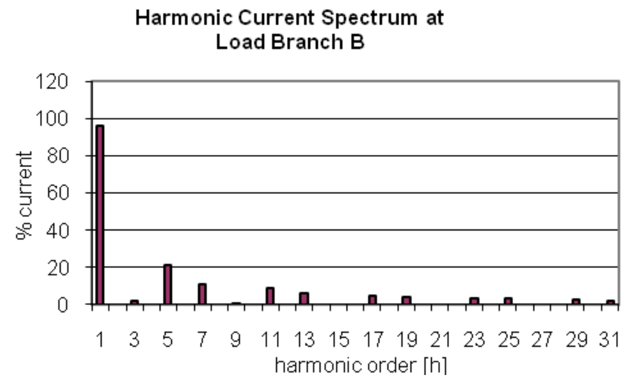
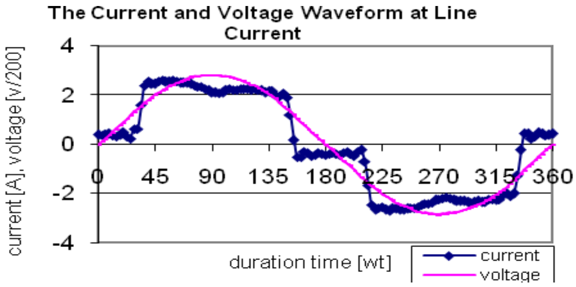




Fig. 6. The current and voltage waveforms and harmonic currents spectrum at load branch A and B after minimization

Figure 7 and 8 shows the comparisons results between before and after minimization at line current, PCC. These results indicate that the current waveform is a sinusoidal waveform.
Also, it shows that the magnitude of harmonic currents for the 5th and 7th order is reduced by 25% and 10%, respectively.



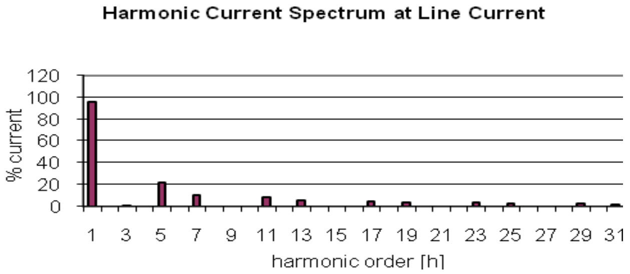
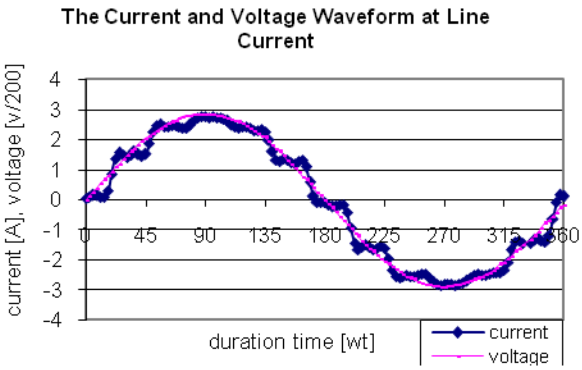




Fig. 7. The current and voltage waveforms and harmonic currents spectrum at line current, PCC before minimization



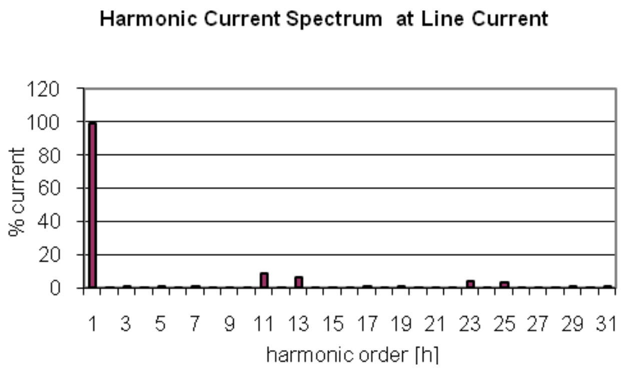



Fig. 8. The current and voltage waveforms and harmonic currents spectrum at line current, PCC after minimization

## IV. CONCLUSIONS

The results show that the harmonic currents reduction for 5th and 7th orders are significantly reduced by 25.0% and 10.0% respectively. It will be caused THDi at line currents was improved 16.7% and simultaneously the line current has changed from a distortion to a sinusoidal waveform.

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