Applications of Zigzag Transformers to Reduce Harmonics in Distribution System

Abstract. This paper presents a scheme of the zigzag transformer for reducing the neutral current and investigates by means of simulations the performance of a zigzag transformer on a three-phase diode bridge rectifier in order to reduce line current harmonics. This application is carried out in a 23 kV-220/127 distribution system. The first scheme is based on the installation of a zigzag transformer between the transformer-secondary lines and the neutral of the same transformer. For the second scheme the zigzag transformer is installed between the transformer secondary lines and the diode bridge. For the first scheme, the research considers two connections for the transformer, delta-star grounded, and star-star grounded. Both schemes are very effective reducing the current harmonics. In the last part we analyze the third harmonic in the delta winding of transformers.

Keywords: harmonics, neutral conductor, zigzag transformer, distribution system, three-phase diode bridge rectifier

1. Introduction. The zigzag transformer has been used some years ago for creating a neutral, thereby converting a three-wire distribution system to a four-wire system [1]. The connections for a zigzag transformer are shown in Figure 1. Figure 2 shows a phasor diagram for a zigzag connection.

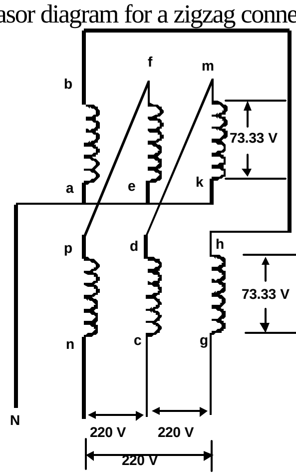

Figure 1. Zigzag connection with a neutral grounded or Interconected-star connection

The voltage relations for the zigzag transformer are given by [2]:

$$V_{gN} = \sqrt{3}V_{bN} \quad (1)$$

$$V_{gn} = \sqrt{3}V_{gN} \quad (2)$$

$$V_{gn} = 3V_{bN} \quad (3)$$

The star and the zigzag connections offer the opportunity to connect the neutral point of the transformer windings to the system neutral [3]. If the neutral is grounded, the connection is referred to as a *grounded-neutral connection*. If the primary is not an effectively grounded system, the permissible connections are delta-star grounded, delta-zigzag grounded and star-zigzag grounded. The star grounded- star grounded should not be used except on 4-wire effectively grounded primaries.

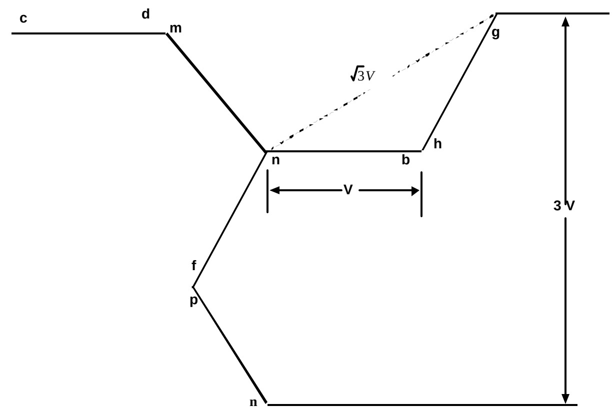

Figure 2. Phasor diagram of the zigzag transformer

The contribution of this paper is the application of the zigzag transformer considering several connections to reduce harmonic in neutral conductor. In order to see this change we are going to simulate the system before and after de connection of the zigzag transformer. The systems required three 5 kVA transformer to form the zigzag transformer. The rating of these units is based on the line voltage and the unbalanced current in the neutral [4]. For the second scheme, the circuit consists of a three-phase diode bridge rectifier; the simulations show how the current harmonics are reduced when a zigzag transformer is installed. The harmonics produce overheating in the transformer and the neutral conductor suffers from overheating due to third harmonic currents. The effect of harmonic currents is the increases of ohmic losses of the current-carrying conductor. This is due to (a) an increase in current-carrying components and (b) an increase in conductor resistance due to frequency dependence (skin effect). Other solutions to this problem can be found in [5], [6], [7], [8]. These schemes that this paper present are good solutions in some cases, because zigzag transformers have been built since many years ago and have no electronic devices or moving parts. If transformers are not overloaded such that their insulation is maintained, they will last 25-30 years. Some active filters and others new harmonic mitigation devices have yet to "stand the test of time". This paper use a version of EMTDC/PSCADA V3 to simulated the proposed schemes.

2. Description of the proposed scheme

Non-sinusoidal currents generate harmonics that induce additional heating losses in the transformer core, windings, and conductors. This additional heating reduces the efficiency of the transformer and accelerates the loss of life of the insulation.

Third harmonics currents add up in the neutral conductor of the distribution system feeding on-linear loads such as personal computers and electronic office machines with switch of power supplies. The neutral conductor suffers from overheating because the third harmonics current from the three phases do not cancel within the conductor. The zigzag transformer has been used in the past for creating a neutral, thereby converting a three-phase, four-wire system. The zigzag transformer is used to share the load neutral current, since there are two trajectories for the current [9]:

(a) To the distribution transformer
(b) To the zigzag transformer

The zigzag transformer presents a low-impedance path to ground for zero-sequence currents and therefore ground current flows with any shift of the system neutral [3].

In three-phase circuits third harmonic currents add rather than cancel in the neutral and can be as much as 1.7 times the phase current for converter loads. The neutral current i_N of a star connection in Figure 3 contain only the sum of zero sequence current components found in the phase currents multiplied by three,

$$i_N = \sum_{n=3,6,9,...} I_n \sin(nwt - q_n) \qquad (4)$$

According with [10] 22.6 % of the sites had neutral current in excess of 100 % of the phase current. Since the neutral conductor is usually sized the same as the phase conductors, the neutral conductor can be overloaded. The problem is most likely to occur in commercial buildings where a three-phase distribution system feeds large single-phase electronic office equipment loads.

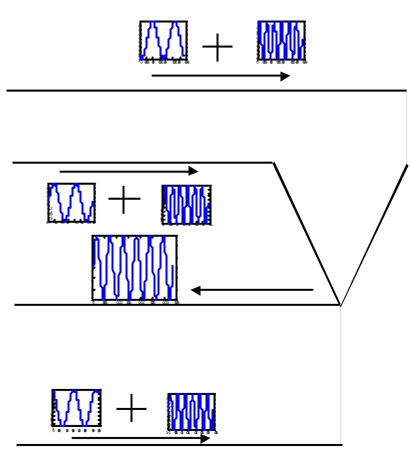

Figure 3. Third harmonic of line currents and the neutral current

Harmonics in major commercial buildings are a matter of concern. High levels of third harmonics give rise to excessive neutral currents. High values of neutral current have been found in some systems, see Figures 4-7.

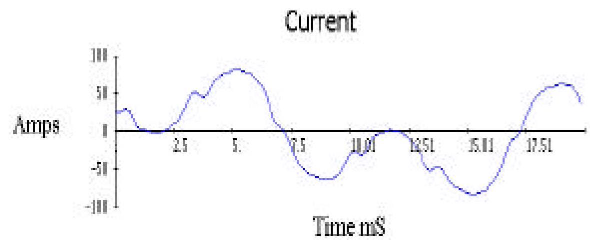

Figure 4. Typical neutral current in high-rise office building [11]

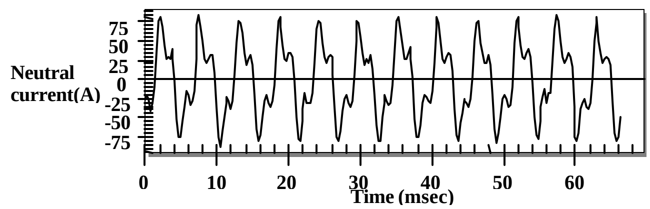

Figure 5. Measurement of neutral current in the neutral of a 13.8/240 volt 500 kVA transformer under no-load conditions [12]

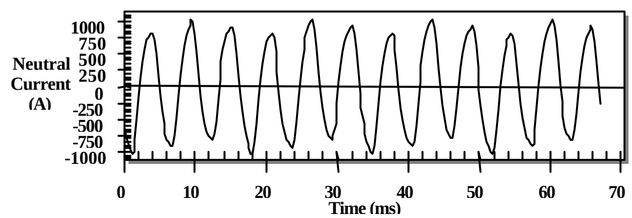

Figure 6. Measurement of neutral current in the neutral of a 13.8/240 volt 500 kVA transformer under rated-load conditions [12]

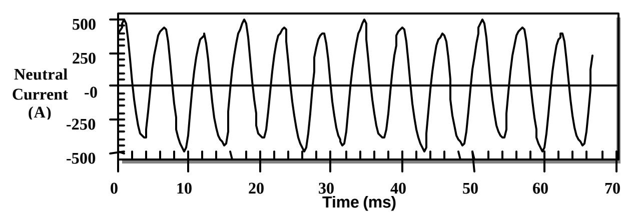

Figure 7. Measurement of neutral current in the neutral of a 13.8/240 volt 500 kVA transformer without part of load [12]

Grounding a system at more than one point would lead to the circulation of harmonics via the multiple ground points. The third-harmonics voltages of the three-phase system are in phase with each other if two points of the system are grounded currently, the third-harmonic voltages will produce circulating current. It is the harmonic currents on the neutral system, which cause most problems of interference with communication circuits.

The zigzag transformer can be combined with either star or delta connections in two-winding transformer, in this application only the delta-zigzag winding is used. The goal of installing a zigzag transformer is to share the neutral current. The factor that influences how is share the neutral current is the impedance of the paths. Sometimes is convenient to put impedance in the neutral, thus allowing the current to split into two paths, one to the distribution transformer, and the other to the zigzag transformer.

The excitation of the distribution circuits in this paper is shown in Figure 8. It is observed that the mean value of the third harmonic component (due to non-liner loads) is considerable with respect to the fundamental component. Flat topping of the waveform can result due to the impedance of the power system at the harmonic current frequencies.

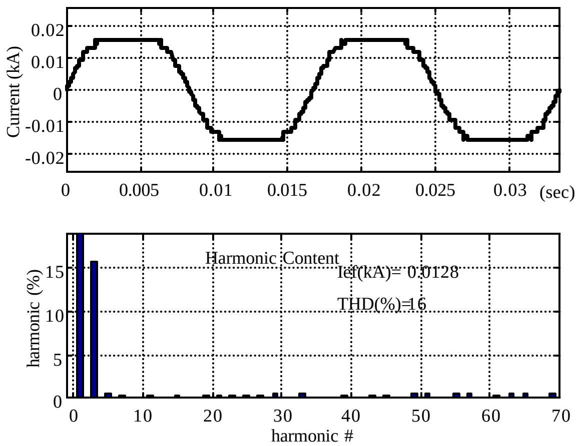

Figure 8. Distribution-circuit source

In general, the rms of a waveform, based on its harmonic component, is given by [13],

$$I_{ef} = \sqrt{I_{DC}^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + \cdots} \qquad (5)$$

For symmetrical waveforms, (5) is reduced to the following expression [13],

$$I_{ef} = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_{11}^2 + \cdots} \qquad (6)$$

Component harmonic can be represented as a percentage of the fundamental component or as a percentage of the rms value of the waveform. In these simulations is used the first representation.

3. Behavior of the neutral current before and after de installation of the zigzag transformer

Table 1 shows the values of neutral current before and after de installation of zigzag transformer. The table 1 indicates that the reduction of neutral current after the installation of zigzag transformer was close to 100 % in the two connections considered.

Table 1. Neutral current with and without zigzag transformer

Connection	Without zigzag transformer	With zigzag transformer (A)	Change percentage
Delta-star grounded	0.4	0.266	99
Star-star ground	14.6	0.101	99

Figure 9 and 10 shows the neutral current before and after the installation of zigzag transformer. Beside the harmonic spectrum is shown for each current waveform. Figure 11 shows the test circuit of star –star ground with a zigzag winding installed.

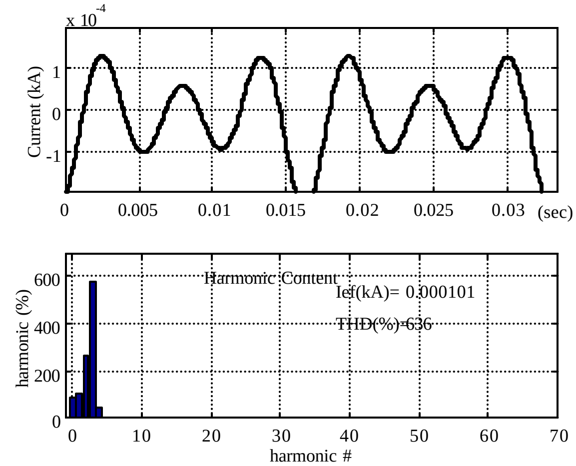

Figure 9. Star-star grounded transformer neutral current with zigzag transformer

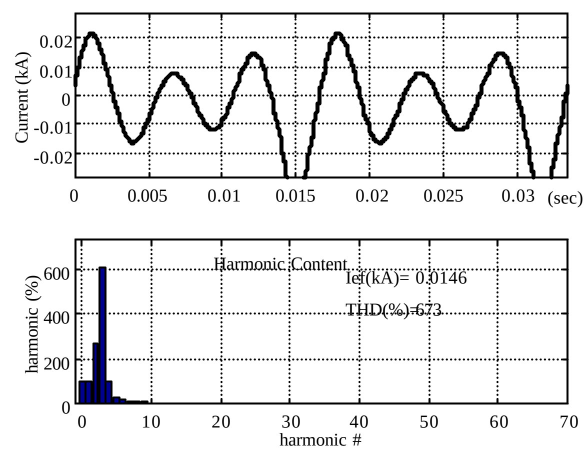

Figure 10. Star-star grounded transformer neutral current without zigzag transformer

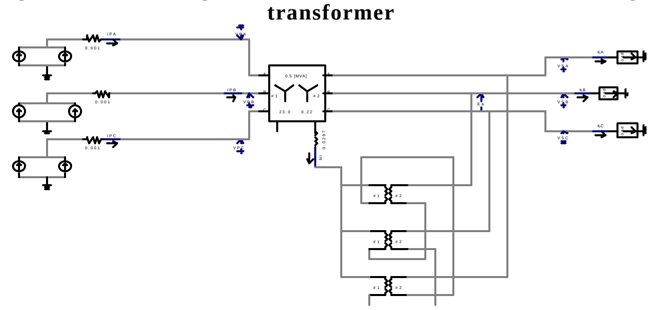

Figure 11. Test circuit of star-star grounded with the zigzag transformer installed.

4. Reduction of current harmonic in a circuit that contains a three-phase diode bridge rectifier

To create a harmonic load for the transformer test, the load includes a diode bridge. This load circuit was designed to simulate a severe harmonic load condition.

Table 2 shows the effective current and the THD for three test circuits. This table shows the effect of the zigzag transformer on the value of I_{ef} and THD with respect to the case without zigzag transformer.

Table 2. Behavior of the line current before and after the installation of zigzag transformer

Connection	Without zigzag transformer	With zigzag winding[1]	With zigzag transformer
I_{ef} (A)	24.4	31.7	26.6
THD (%)	33.2	20.2	11.6

Table 3 shows the line-current harmonics before and after the connection of the zigzag transformer. The case with a delta-zigzag transformer reduces more the harmonic content that with zigzag winding. The delta winding of the zigzag transformer of figure 17 trap the zero sequence third harmonic current to circulate and this connection reduce more the THD and as a consequence the magnitude of harmonic component.

Table 3. Comparison of harmonics in the line current

Harmonic	Without zigzag transformer	With zigzag winding[1]	With zigzag transformer
5	30.94	18.03	8.44
7	1.13	7.24	7.19
11	6.41	3.11	2.59
13	4.81	2.64	1.34
17	4.19	1.47	0.89
19	3.50	1.60	0.75
23	3.08	1.00	0.44
25	2.67	1.11	0.52

According with table 3, the scheme described in this paper provides a simple solution to the line current distortion associated with a three-phase bridge rectifier.

Figures 13, 15 and 17 show the test circuit for the several cases considered in table 2 and 3 and figures 12, 14 and 16 show the corresponding waveform of current and the harmonic spectrum.

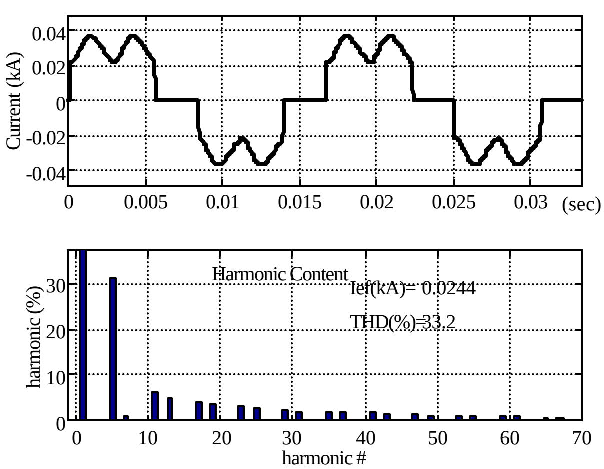

Figure 12. Waveform of the secondary current (ILA) and harmonic spectrum for figure 13.

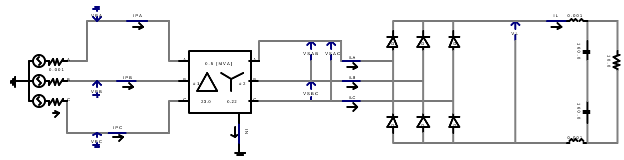

Figure 13. Test circuit without zigzag transformer

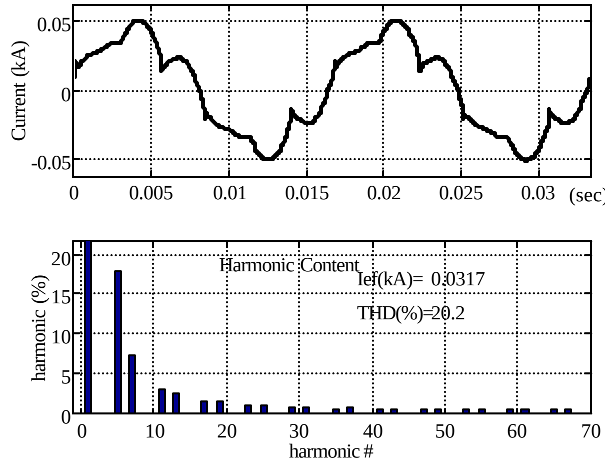

Figure 14. Waveform of the secondary current (ILA) and harmonic spectrum for figure 17.

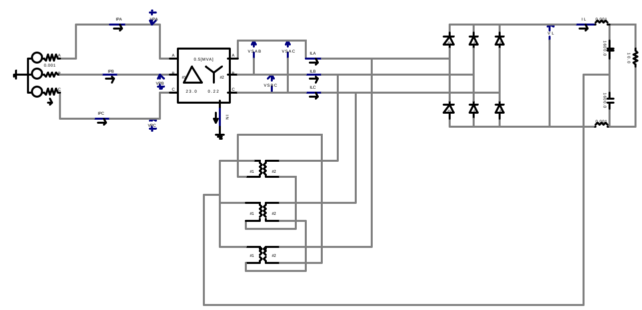

Figure 15. Test circuit with a zigzag winding

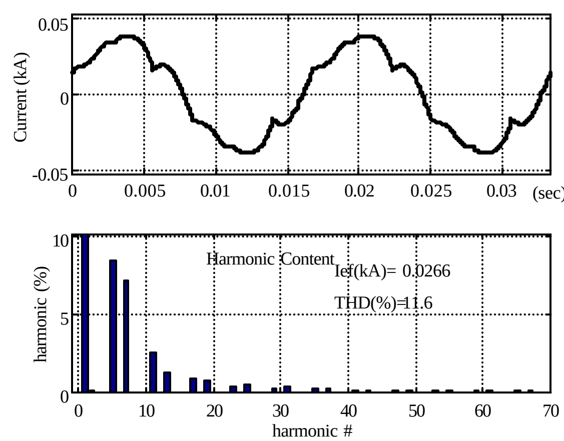

Figure 16. Waveform of the secondary current (ILA) and harmonic spectrum for figure 15.

[1] The primary winding of the zigzag transformer is not included.

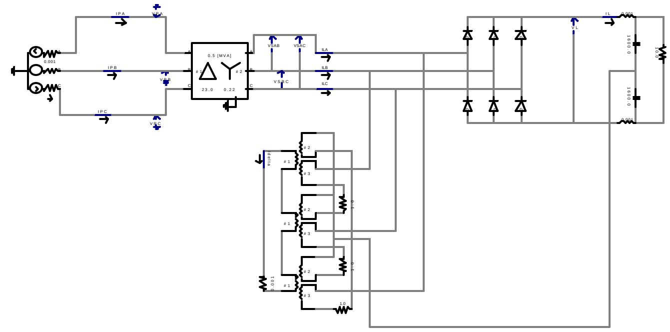

Figure 17. Test circuit with a zigzag transformer (the primary winding is connected in delta)

4. The third harmonic trapped in the delta

In this section is simulated a small distribution system in order to observe the third harmonic of current inside of delta-connected primaries and secondaries. In both simulations the system used and the excitation is the same (the only thing changed is the transformer connection). In this section the test circuit of Figure 18 is used.

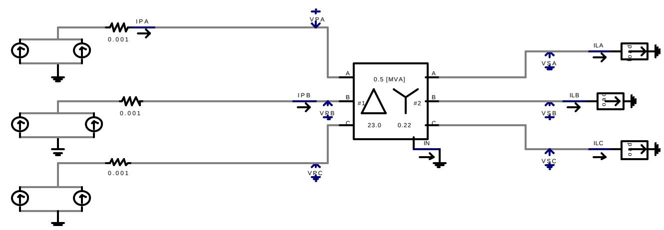

Figure 18. Test circuit of of delta-star grounded transformer

In Figure 19 the percentage of third harmonic trapped in the delta side is 18 % with respect to the fundamental. In Figure 20 the percentage of third harmonic trapped in the delta side is 0.7% with respect to the fundamental.

According to [14] "The third harmonic remain trapped in the delta and do not show up in the line current on the delta side" The question in this case is: Why the third harmonic is so large in the star grounded-delta transformer compared to the delta-star grounded connection?

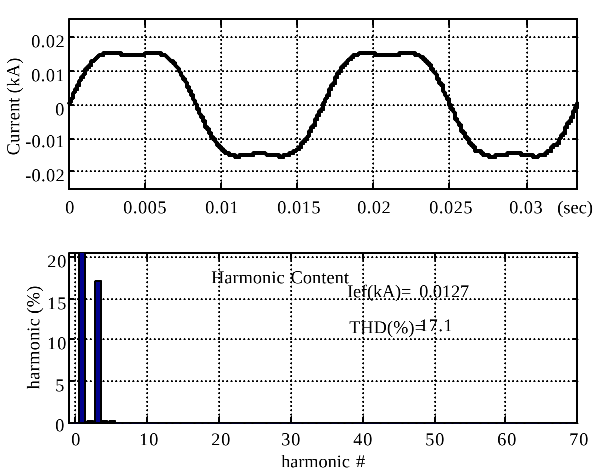

Figure 19. Secondary delta current of star grounded -delta transformer (Phase AB)

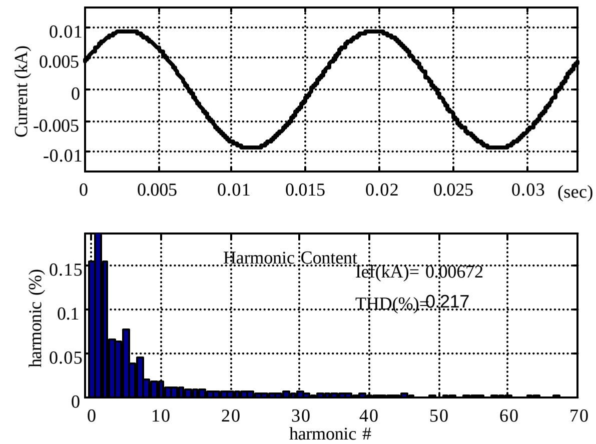

Figure 20. Primary delta current (phase AB) of delta-star grounded transformer

Case: star grounded-delta. The currents injected (including harmonic current) by the source flow on the star. For this reason are induced the third harmonic on the delta. In other words, if there are harmonic components in the primary winding of a transformer, the secondary winding will has these harmonic components transformed by the turn ratio (Faraday's law.). In any star connection the instantaneous sum of the current flowing to and from the common point is zero. But, when the connection is star ungrounded-delta the sum of the current in the star point would therefore not be zero, and consequently in symmetrical three-phase, star ungrounded third harmonic currents cannot exist. This mean, that when the connection to ground of the start is open there are not third harmonic inside the delta loop on the secondary side.

Case delta- star grounded. The small system has a balanced-current source, and then the sum of currents at fundamental frequency is zero at delta loop (super node). The third harmonic cannot flow and it does not enter to the delta. For this reason the third harmonic inside the delta is small. There is no place for the third harmonic current to go in the delta connection because the magnitude of the zero-sequence impedance looking into a delta-connected transformer is infinite [15].

Delta- star grounded transformer are an effective means of reducing zero sequence harmonic currents from the secondary to the primary side of the transformer because the triplen harmonics circulate in the delta (primary side) of the transformer and do not show up on the line side of the transformer. In order to see more details about this application consult [16].

But, what are the advantages and disadvantages of connecting the high-voltage system to ground? The main advantages of connecting a high-voltage system to ground are [1]:

(a) A ground neutral allows rapid operation of protection immediately a ground fault occurs on the system.

(b) If the neutral is solidly grounded, the voltage of any live conductor cannot exceed the voltage from line to neutral.

The only disadvantage of connecting a high-voltage system to ground is that this introduces the first ground from the outset and it thus increases the susceptibility to ground faults.

5. Conclusions

This paper presented a scheme of the zigzag transformer for reducing the neutral current in a 23 kV-220/127 V distribution system. The research considered two connections for the transformer, delta-star grounded, star-star grounded. The scheme is very effective reducing the neutral current from almost 100 % in all the cases. The second scheme applied the zigzag transformer in order to reduce the current harmonic. The best result was obtained when the zigzag transformer had winding primary connected in delta.

In the last part we showed when the delta winding of the transformer could *trap* third harmonic of current. The neutral conductors usually are sized like the phase conductors, can still be overloaded since the neural current can exceed the rated phase current. The magnitude of the neutral current in three-phase power system depends on the harmonic content and the load currents. The lack of monitoring of power system difficult anticipates high current in the neutral conductors. The monitoring is necessary because changes make to the power system may produce high neutral currents.

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