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Research Article

Three to Nine Phase Conversion Transformer, Modelling, Simulation and Harmonic Evaluation for Unbalanced and Nonlinear Loads

Majid Nayeripour [a] , Mohammad Esmaeil Hassanzadeh[a*], Hossein Fallahzadeh Abarghouei [a]

[a] Department of Electrical and Electronics Engineering Shiraz University of Technology, Shiraz, Iran
* Corresponding author. Tel.: +987117354500-4, (Ext. 2748);
E-mail address: M.hasanzadeh@sutech.ac.ir

A b s t r a c t

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Transformer,
Nonlinear Load,
Harmonic,
Total Harmonic Distortion.

In many industrial applications a nine-phase ac supply is needed. So there is strong motivation to develop a system which convert available three-phase supply to multiphase supply such as nine-phase one. Several methods like using motor-generator sets, power converter, multilevel converter, etc. have been proposed before but in this paper a more practical transformer based topology which converts voltage of usual three phase supply to nine phase is presented. Simple design and implementation for high rating, pure sine wave and fewer harmonics are the salient features of the proposed model. Nine-phase static voltage supply with fixed voltage and frequency can be used for RL and nonlinear loads which produce current and voltage harmonics in the distribution systems. Complete design and simulation of the proposed structure with analytical calculation for nonlinear load is presented. Finally, the effectiveness of the proposed transformer connection for reducing total harmonic distortion is verified using MATLAB/SIMULINK software.

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1. Introduction

The research on multi-phase (more than three phase) systems because of their importance in industrial application has been more considered recently. Nine-phase power supply systems as a kind of multi-phase system are investigated in various aspects such as power generation, power transmission and power consumption areas [1]. Some researches on multiphase generators are available in the literature [2-4]. In addition the research on multi-phase converters has been significantly increased since the beginning of this century because of development in power electronic devices and digital signal processors. Detailed reviews on the multiphase drives are available in [1, 5, 6]. In [7] a new type of transformer, which is converting three phase to five-phase system is presented. This research only focus on modeling and controlling multi-phase electric drives power converters. Also, a static multiwinding transformation system to change the phase number from three to nine-phase has been introduced.

This paper presents a static convertor which is based on transformer connections. A particular connection of transformer with reduced windings to convert three-phase supply which is available in the power networks, to nine-phase is proposed. In the proposed connection, the current harmonics of nonlinear loads such as bridge rectifiers in industrial applications which drawn from source are reduced significantly.

Simple design and implementation for high rating pure sine wave output and decreasing the number of secondary windings and harmonics reduction are contributions of this paper in compare with other recent works. a nine phase source using special transformer connection is presented In [8], but it has not showed any harmonic analysis and the connection is not as simple as our work. Nevertheless, the analysis and design are completely different.

The paper is organized as follows: section 2 demonstrates winding arrangement for nine-phase output. Implementation of proposed model and balanced waveforms of a nine-phase output voltages are evaluated in section 3. In section 4, three cases study consisting three-phase bridge rectifier with balanced and unbalanced RL load as a nonlinear load and current source include third harmonic, have been considered for harmonic reduction validation. The paper is concluded in the final section.

2. Winding Arrangement for Nine phase output

Three separate transformer cores with a primary winding and 4 secondary windings are considered. Six terminals of primaries are connected in star or delta connections and the 24 terminals of secondaries are connected in a manner to produce nine phase. Star connection of primary is discussed here. The delta connection of the primary is also similar to star. The connection type of secondaries is illustrated in Figure 1 and the corresponding phasor diagram is represented in Figure 2. The turn ratios between different phases are given in Table 1.

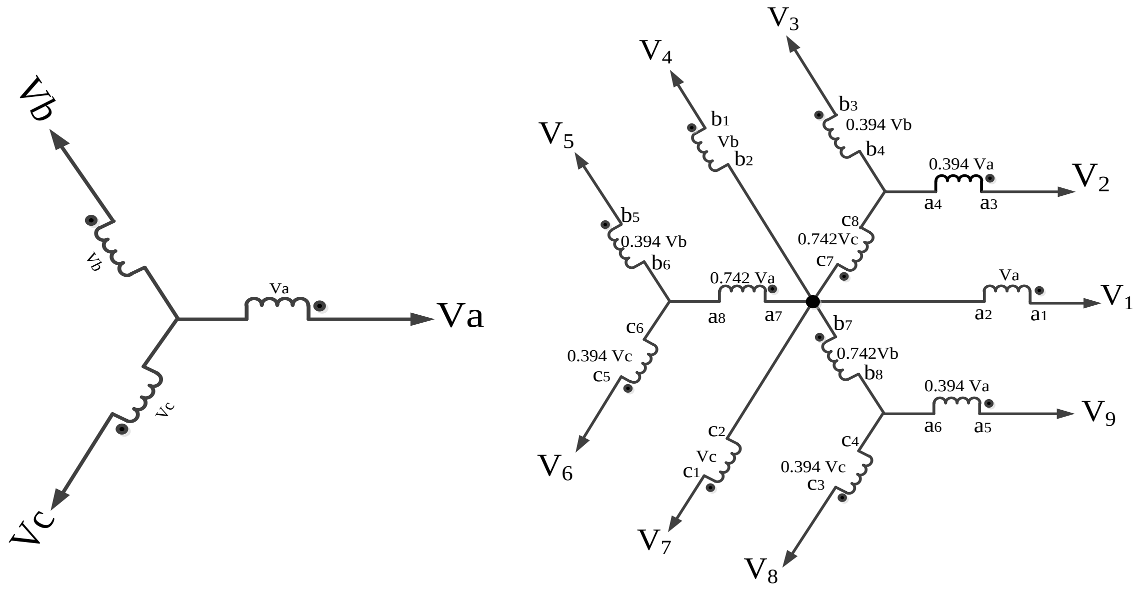

Fig. 1: Connection of primary and secondary windings

The input phases are represented with letters “a”, “b” and “c” and the outputs are represented with numbers “1”, “2”, “3”, “4”, “5”, “6”, “7”, “8”, “9”.The output phases with required phase angles of 40° between each phase is obtained using appropriate turn ratios, and the phasor equations are illustrated from (1) to (13). The turn ratios in all three phases are identical and the choice of turn ratio is the key in creating the required phase displacement in the output phases.

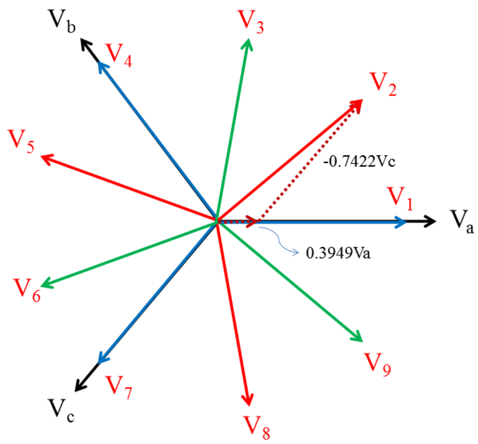

Fig. 2: Phasor diagram of the proposed transformer connection

As illustrated in Figure 2, the output phase “V1”, “V4” and “V7” is along the input phase “Va”, “Vb” and “Vc” respectively. The output phase “V2” is phasor summation of winding voltage “0.394Va” and “0.742Vc”, the output phase “V3” is obtained by the phasor summation of winding voltages “0.394Vb” and “0.742Vc”, “V5” is phasor summation of “0.742Va” and “0.394Vb” ,“V6” is obtained by the phasor “0.742Va” pluse “0.394Vc” , “V8” is phasor “0.742Vb” pluse “0.394Vc”,and finally “V9” is obtained by the phasor addition of winding voltages “0.742Vb” and “0.394Va”.so,all nine phases are established.

Table. 1: Turn ratios: secondary turns (Ns) to primary turns (Np)

Primary	Secondary	Turn Ratio (Ns/Np)
Phase a	a1 a2	1
	a3 a4	0.3949
	a5 a6	0.3949
	a7 a8	0.7422
Phase b	b1 b2	1
	b3 b4	0.3949
	b5 b6	0.3949
	b7 b8	0.7422
Phase c	c1 c2	1
	c3 c4	0.3949
	c5 c6	0.3949
	c7 c8	0.7422

The transformation from three to nine-phase and vice-versa can be obtained using the following equations (1-13).

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \\ V_9 \end{bmatrix} = \frac{1}{Sin(\frac{\pi}{3})} \begin{bmatrix} 1 & 0 & 0 \\ Sin(\frac{\pi}{9}) & 0 & -Sin(\frac{2\pi}{9}) \\ 0 & Sin(\frac{\pi}{9}) & -Sin(\frac{2\pi}{9}) \\ 0 & 1 & 0 \\ -Sin(\frac{2\pi}{9}) & Sin(\frac{\pi}{9}) & 0 \\ -Sin(\frac{2\pi}{9}) & 0 & Sin(\frac{\pi}{9}) \\ 0 & 0 & 1 \\ 0 & -Sin(\frac{2\pi}{9}) & Sin(\frac{\pi}{9}) \\ Sin(\frac{\pi}{9}) & -Sin(\frac{2\pi}{9}) & 0 \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

$$V_1 = V_{\max} Sin(\omega t) \qquad (2)$$

$$V_2 = V_{\max} Sin(\omega t + \frac{2\pi}{9}) \qquad (3)$$

$$V_3 = V_{\max} Sin(\omega t + \frac{4\pi}{9}) \qquad (4)$$

$$V_4 = V_{\max} Sin(\omega t + \frac{2\pi}{3}) \quad (5)$$

$$V_5 = V_{\max} Sin(\omega t + \frac{8\pi}{9}) \quad (6)$$

$$V_6 = V_{\max} Sin(\omega t + \frac{10\pi}{9}) \quad (7)$$

$$V_7 = V_{\max} Sin(\omega t + \frac{4\pi}{3}) \quad (8)$$

$$V_8 = V_{\max} Sin(\omega t + \frac{14\pi}{9}) \quad (9)$$

$$V_9 = V_{\max} Sin(\omega t + \frac{16\pi}{9}) \quad (10)$$

$$V_a = V_{\max} Sin(\omega t) \quad (11)$$

$$V_b = V_{\max} Sin(\omega t + \frac{2\pi}{3}) \quad (12)$$

$$V_c = V_{\max} Sin(\omega t + \frac{4\pi}{9}) \quad (13)$$

3. Simulation Results

The proposed structure is simulated using “simpowersystem” block sets of the MATLAB/Simulink software. The appropriate turn ratios (Table 1) are set in the dialog box. The simulation model is represented in Figure 3 and the output voltage waveforms are illustrated in Figure 4. It is clearly seen that the output is a balanced nine-phase supply for a balanced three-phase input.

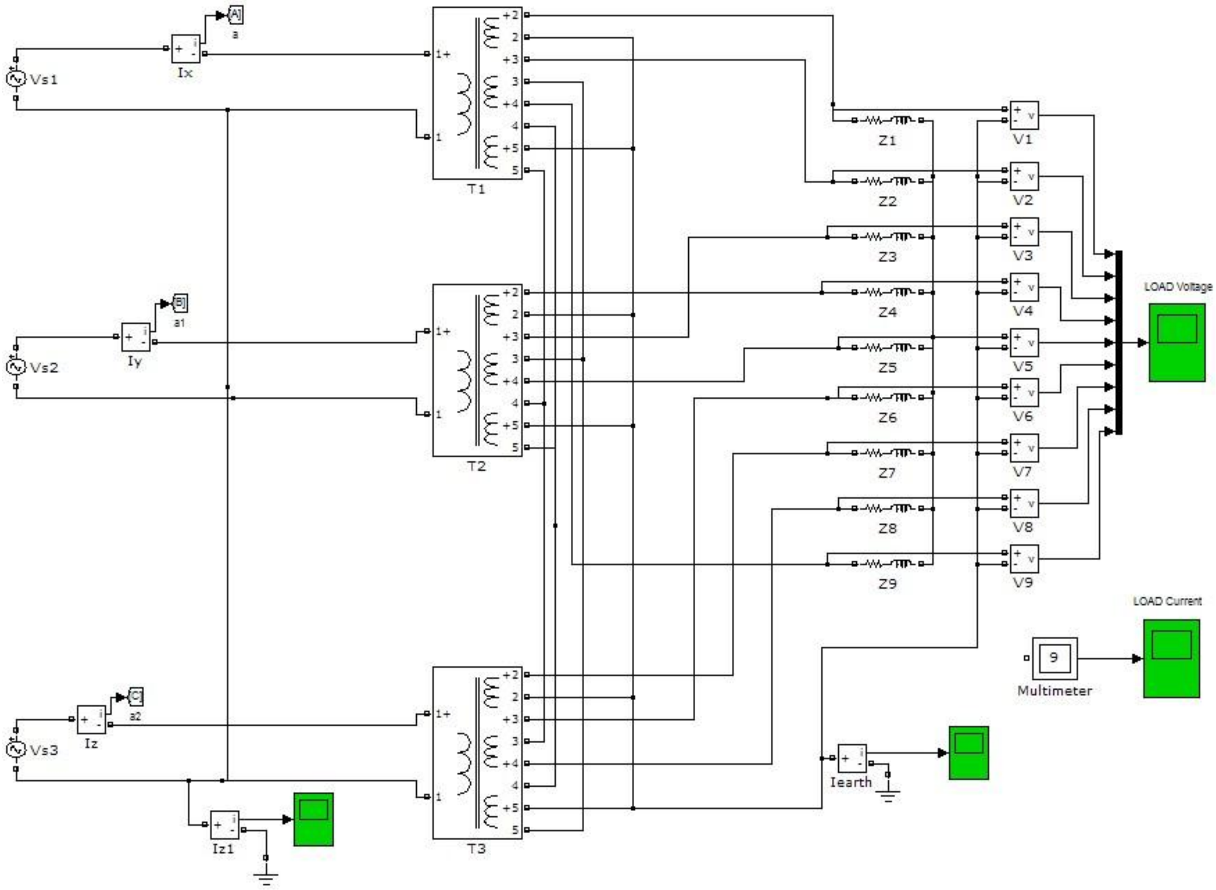

Fig. 3: Simulink model of three to nine phase transformation

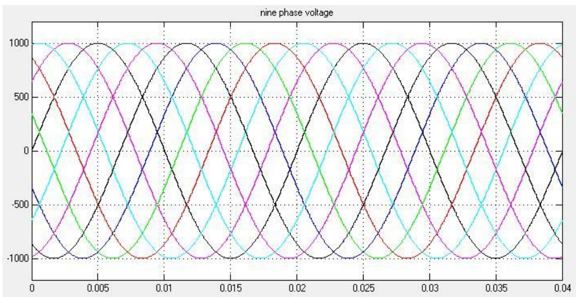

Fig. 4: Balanced nine phase output voltages

4. Harmonic Analysis

Harmonics has been found on 1930s. The main topic was to investigate the effects of harmonics on synchronous machines, communication system and power capacitor. Until last decade the most effort of manufacturer was producing some equipment which sustains the harmonics and can mitigate interaction effects. But in the last decade of 1970s during the consideration and investigation on power system in order to decrease the grid loss, the utility company engineers realized that this equipment will damage the grid. Harmonics are mainly produced by nonlinear elements such as drivers, power electronic converters, etc.

In nonlinear elements, current-voltage relationship is nonlinear and an increasing in voltage may cause the current becomes double or current waveform has been changed. Generally nonlinear elements produce current with harmonic and this current will cause voltage harmonic. These harmonics will cause interference in phone lines, remote control systems, etc. voltage and current harmonics can also have negative impact on the performance of protective relays and measurement devices [9, 10]. These interferences may have technical and economic disadvantages for the grid.

One of the contributions of the paper is type of the connections which decreases the number of secondary windings in compare with recent works. The other one is harmonic reduction in currents which is drawn from the source in nonlinear loads. To show the effectiveness of proposed method, three case studies are considered.

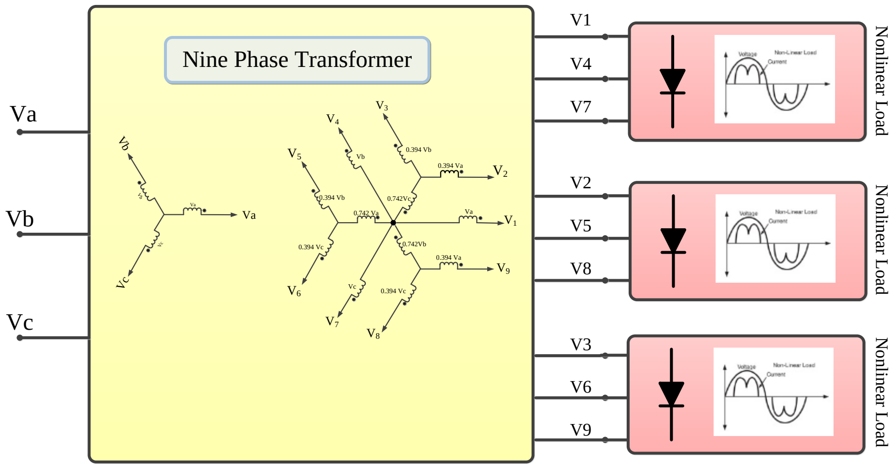

Fig. 5: Nonlinear loads supplied by proposed nine phase transformer

4.1 Case study 1

Three-phase bridge rectifier with RL load is considered as nonlinear load. There are three nonlinear loads. The first nonlinear load is supplied through V1, V4 and V7 with 120° Phase difference to each other, similarly the second nonlinear load is supplied through V2, V5 and V8 and finally the last nonlinear load is supplied through V3, V6 and V9 as illustrated in Figure 5. The loads are the same (26 kW and 2.5 kVAR). The current waveform which is drawn from the source and its harmonic is illustrated in Figure 7. To evaluate these results we consider a case which three individual transformers, supply three nonlinear loads with same parameters similar to before as illustrated in Figure 6. In this case, current waveform which is drawn from the source and its harmonic content is illustrated in Figure 8. It can be seen form Figure 7 that THD in the input current of nine-phase transformer is equal to 4.37 percent whereas THD in the input current of 3 three-phase transformer system is equal to 21.15 percent of the fundamental frequency. So the results show that THD in proposed system is reduced by almost 5 times.

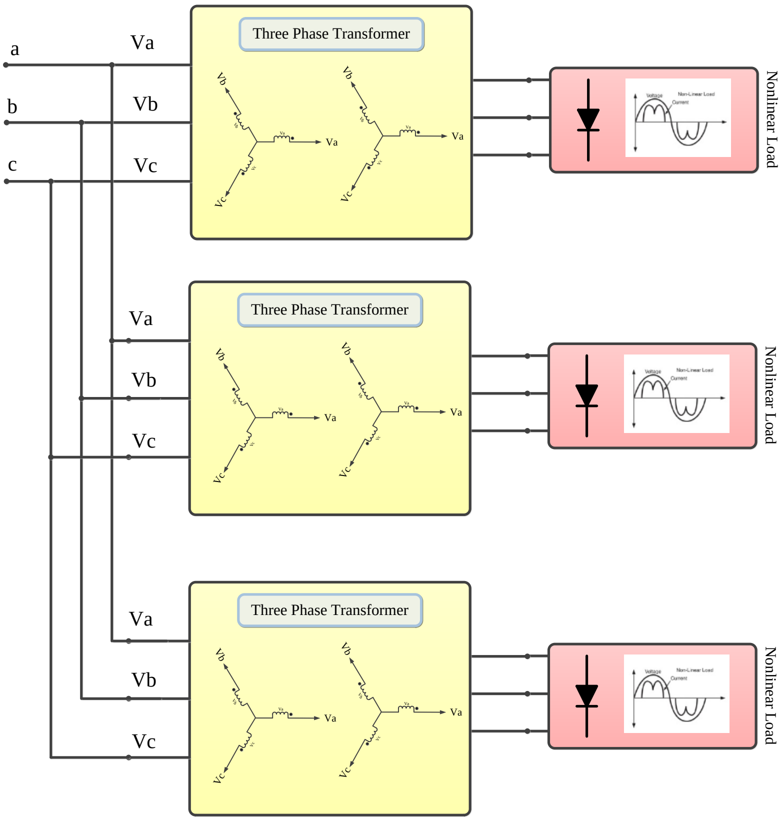

Fig. 6: Nonlinear loads supplied by 3 three-phase transformer

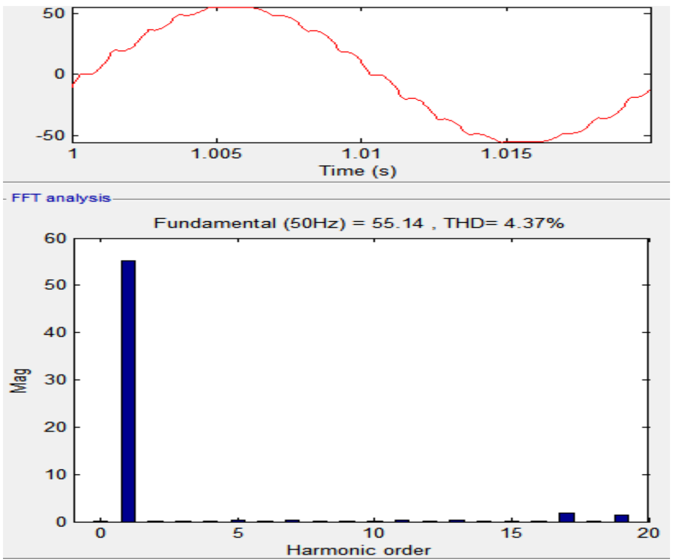

Fig. 7: Nine phase transformer's input current and its harmonic content

Additionally it can be seen form Figure 7 and 8 that fifth harmonic in the input current of nine transformer is less than 1 percent whereas fifth harmonic in the input current of the 3 three phase transformer system is equal to 18.4 percent of the fundamental. The results show that fifth harmonic in proposed system is reduced by almost 18 times. The same result can be concluded for other harmonics order.

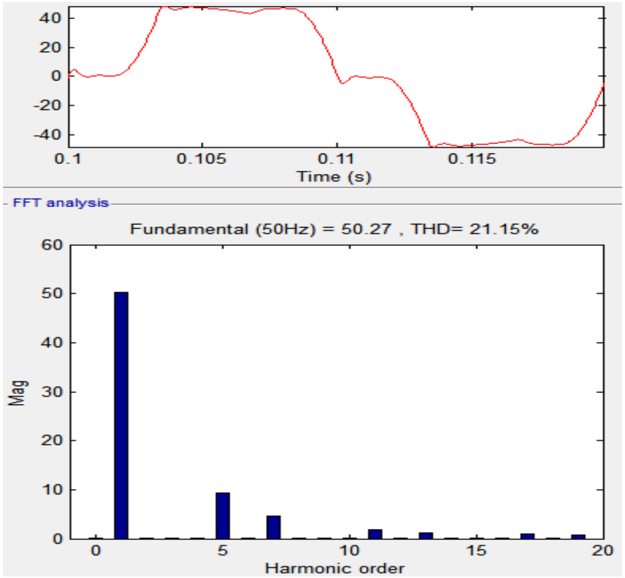

Fig. 8:. Three phase transformer's input current and its harmonic content

4.2 Case study 2

In this section, current source include third harmonic with the amplitude of 1/3 of the fundamental is used as nonlinear load. There are three similar nonlinear loads. The first nonlinear load is supplied through V1, V4 and V7 with 120° phase difference to each other, similarly the second nonlinear load is supplied through V2, V5 and V8 and finally the last nonlinear load is supplied through V3, V6 and V9.

It can be seen form Figure 9, 10 that THD in the input current of nine-phase transformer is equal to 3.86 percent whereas THD in the input current of 3 three phase transformer system is equal to 33.27 percent of the fundamental. The results show that THD in proposed system is reduced by almost 9 times.

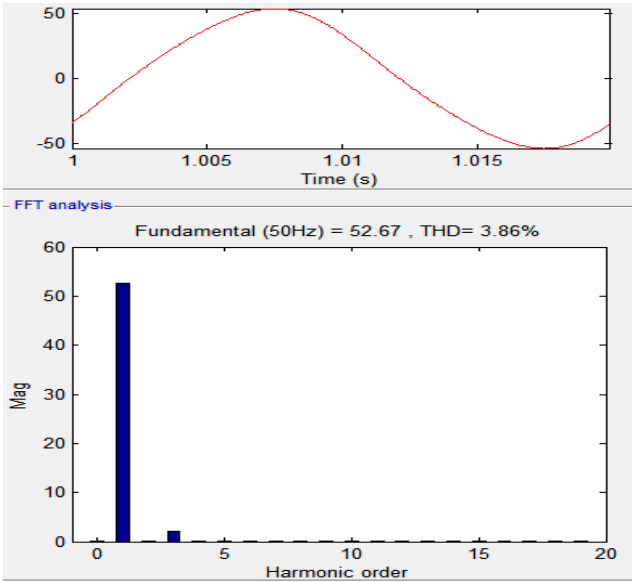

Fig. 9: Nine phase transformer's input current and its harmonic content in case study 2

It can be seen form Figure 10 that third harmonic in the input current of nine transformer is the same as THD, because there isn't any other harmonic in the input current.

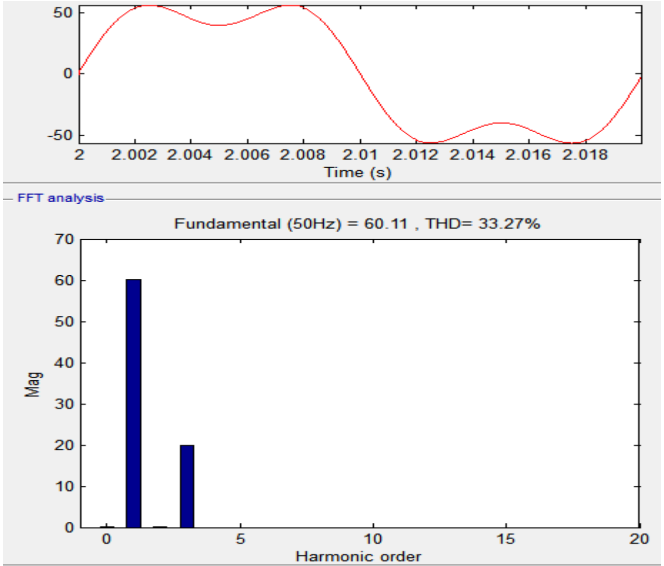

Fig. 10: Three phase transformer's input current and its harmonic content in case study 2

4.3 Case study 3

In this case, three-phase bridge rectifier with RL load is used as nonlinear load. There are three nonlinear loads with different active and reactive power. In fact in this case impacts of unbalanced loads on the proposed system are investigated.

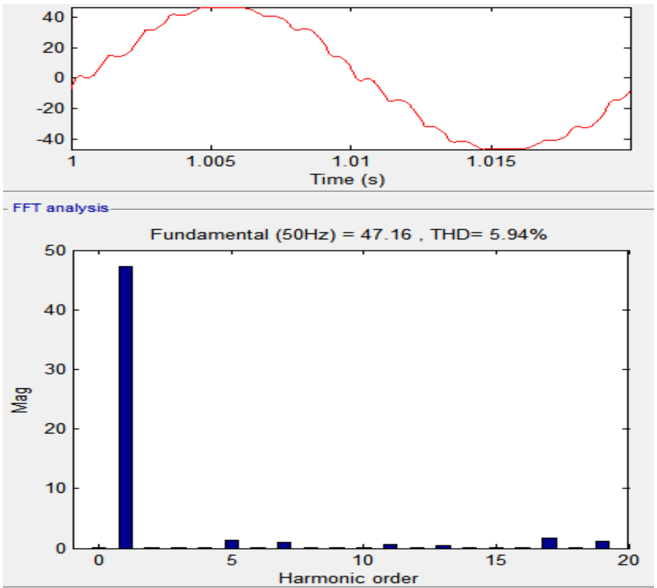

Fig. 11: Nine phase transformer's input current and its harmonic content in case study 3

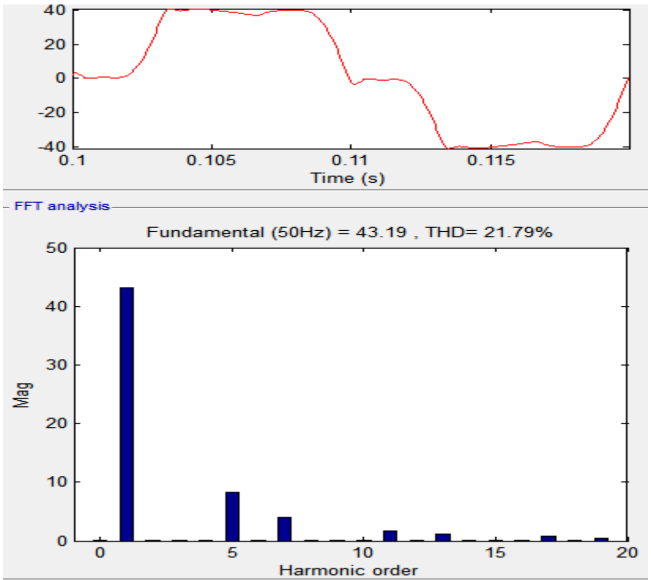

Fig. 12: Three phase transformer's input current and its harmonic content in case study 3

It can be seen form Figure 11 and 12 that THD in the input current of nine-phase transformer is equal to 5.94 percent whereas THD in the input current of 3 three-phase transformer system is equal to 21.79 percent. The results show that THD in proposed system is reduced by almost 3 times. The same results can be deduced for fifth and seventh harmonics. Fifth harmonic in proposed system is reduced by almost 6 times and seventh harmonic is reduced by almost 5 times.

5. Conclusion

In this paper, complete design and simulation of nine phase transformer to supply nonlinear loads which produces current and voltage harmonics in the distribution systems is presented. One of the contributions of the paper was the type of the connections which decreases the number of secondary windings in compare with recent works. Another one was harmonic reduction in current which is drawn from the source in nonlinear loads. Analytical calculations and simulation results using MATLAB/SIMULINK software for nonlinear load show effectiveness of the proposed transformer for harmonics and total harmonic distortion reduction.

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