



Assessment and Modeling of Voltage Harmonics Impacts on Distribution Transformers Considering the Effects of Different Loads

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 8 June 2019 Received in revised form 17 August 2019 Accepted 10 September 2019 Available online 11 September 2019</p>	<p>Given the significance of power quality and the substantial impact of harmonics on power systems, evaluating the influence of harmonics on system components and loads is a crucial consideration. The importance of harmonics in power systems has significantly increased with the rising prevalence of nonlinear loads and other high-frequency generating devices. Transformers are one of the primary components in power systems. Supplying nonlinear loads via transformers leads to increased copper and iron losses, higher operational costs, premature insulation failure, and consequently, a reduction in the transformer's useful lifespan. Specifically, when a transformer supplies only linear loads, despite increases in load levels and ambient temperature, its lifespan is not diminished. However, in the case of transformers supplying nonlinear loads, the harmonic currents increase the load levels and losses in the transformer, thereby reducing its lifespan. Accordingly, this paper analyzes and evaluates the impact of harmonic distortion on a 630 KVA Y-Y connected distribution transformer under both linear and nonlinear load conditions. The evaluation demonstrates that the presence of higher-order harmonics significantly increases losses, resulting in a reduction of the transformer's lifespan. To analyze the transformer under harmonic conditions, Simulink/MATLAB software was employed.</p>
<p>Keywords: Harmonic Voltage and Current, Distribution Transformers, Nonlinear Load, Harmonic Distortion, Transformer Lifespan</p>	

1. INTRODUCTION

In recent years, harmonics in power systems have significantly increased due to the rise in nonlinear loads, making it a major topic of discussion in power systems. Currently, the widespread use of power electronic equipment in power converters, high-voltage DC systems, nonlinear loads, and renewable energy sources (e.g., wind farms and photovoltaic power plants) has substantially heightened the importance of power quality assessment. These developments have introduced unintended harmonic effects in the distribution network, necessitating thorough evaluations of power quality [1].

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The advent of power electronics has led to the extensive spread of nonlinear loads across modern societies, from heavy industrial to commercial applications. This proliferation generates harmonic currents and voltages that impact the power system and its equipment, particularly transformers. For instance, the proportion of nonlinear loads in the United States has surged from 5% in 1960 to 95% in 2010 [2]. Transformers, being a fundamental component of power systems, directly influence stability, safety, and reliability, requiring routine maintenance to prevent power outages in distribution networks.

Network harmonics have a detrimental impact on distribution transformers. Given the substantial initial costs of transformers and the potential network connection issues during their replacement, protecting transformers to mitigate lifespan reduction is crucial. Hence, assessing the impact of current harmonics on the overall performance of distribution transformers is vital for network design and maintenance [3-4].

Extensive studies have been conducted in this area, with key studies highlighted below:

In reference [4], the effects of harmonic distortion of load current and voltage on distribution transformers are discussed. It provides standard methods for calculating harmonic effects and designing and developing K-Factor transformers capable of operating under specific harmonic environments. Reference [5] discusses the impact of harmonics on transformers and presents a thermal model to predict the transformer's hot spot temperature. Reference [6] examines the effects of nonlinear loads on transformers and the standard IEEE methods for analyzing transformers subjected to distorted currents, using a typical 25 KVA single-phase transformer to demonstrate losses and equivalent capacity.

Reference [7] presents the influence of harmonic current distortion on transformer lifespan, the calculation of the K-factor, and compares findings using Malaysian standards. Reference [8] offers an analysis and evaluation of transformer losses under nonlinear loads, with harmonic data input from a commercial building and calculation of harmonic-induced losses in the distribution transformer. Reference [9] models three typical households with various connected devices to examine the harmonic current spectrum under different network voltage conditions. Reference [10] investigates the no-load performance of distribution transformers under sinusoidal source voltage conditions through a two-dimensional nonlinear transient element analysis considering hysteresis.

Reference [11] emphasizes the importance of studying the impact of current harmonics on distribution transformers for network design and maintenance, exploring the effects of network harmonics on eddy current losses, stray losses, and transformer lifespan. Reference [12] demonstrates the impact of voltage harmonic distortion (THDV) and its spectrum on harmonic loss factors (FHL and FHL-STR) using six-pulse rectifiers with a constant DC power. Reference [13] evaluates the performance of a 100 kVA distribution transformer under harmonic load conditions using the finite element method, showing that increased THD results in higher flux density in the transformer winding and highlighting the accuracy of the finite element method.

Reference [14] presents simulation study results on the impact of harmonics on the lifespan of distribution transformers. Reference [15] uses an oil-immersed distribution transformer to conduct short-circuit and open-circuit tests, discussing the impact of harmonics on electrical parameters. Reference [16] explores the specific effects of voltage harmonics on oil-immersed distribution transformers' losses through laboratory short-circuit and open-circuit tests on aged distribution transformers, indicating significant loss increases.

Reference [17] highlights the need for harmonic and resonance mitigation solutions to prevent damage and avoid network connection issues as nonlinear equipment increases. It reviews common harmonic solutions and new technologies. Reference [18] evaluates the impact on capacity, apparent power, and active energy loss based on real data from a South African medium voltage distribution network, aiming to create a classification tool for local companies to estimate losses and plan based on harmonic distortion levels.

Reference [19] examines the rarely studied impact of voltage harmonics on oil-filled distribution transformers, while reference [20] investigates the effects of various nonlinear loads on a 4.5 kVA, 440/380 V dry-type three-phase distribution transformer, measuring several parameters such as high-order harmonics, current, voltage, active and reactive power, power factor, and total harmonic distortion in a laboratory setting. Reference [21] provides an experimental study on the measurement performance of current and voltage transformers (CTs and VTs) in the presence of harmonics, defining proper testing methods and measurement setups for CT and VT calibration.

Reference [22] offers a thermal impact analysis on transformers, using measured data, transformer parameters, and ambient temperature to estimate the hottest spot temperature and transformer lifespan when supplying linear and nonlinear loads.

Reference [23] presents a simple technique to compensate for the most significant nonlinear effect, harmonic distortion produced by the fundamental voltage. The method, obtained and introduced through numerical simulations, is implemented via suitable experimental tests. Reference [24] reviews energy quality in power systems, an increasingly important topic due to the use of advanced, sensitive equipment.

This paper examines the effects of nonlinear loads in generating harmonics on transformers and the standard IEEE methods for extracting data from transformers subjected to distorted currents. The model parameters are derived from transformer manufacturer test data. This study analyzes and evaluates the impact of nonlinear loads under harmonic conditions on a 630 KVA Y-Y connected distribution transformer. The results of the harmonic impact analysis are implemented and compared using Matlab/Simulink software.

This paper is organized as follows: Section 2 explains the mathematical principles used in the analysis. Section 3 presents the results obtained from the simulation process. Section 4 discusses the simulated results from the distribution transformers. Conclusions are presented in the final section.

2. MATHEMATICAL ANALYSIS OF THE PROBLEM

It is assumed that the network is ideal and the applied voltages are symmetrical, with these voltages at the fundamental frequency having a 120-degree phase difference from each other. Given that only odd harmonics are allowed in the voltage, the instantaneous voltage and current are completely symmetrical and balanced sinusoidally as written below [24]:

$$v_r(t) = \sqrt{2}|V_r|\cos(2\pi ft + \varphi v_r) \tag{1}$$

$$v_s(t) = \sqrt{2}|V_s|\cos(2\pi ft - \frac{2\pi}{3} + \varphi v_s) \tag{2}$$

$$v_t(t) = \sqrt{2}|V_t|\cos(2\pi ft + \frac{2\pi}{3} + \varphi v_t) \tag{3}$$

$$I_r(t) = \sqrt{2}|I_r|\sin(2\pi ft + \varphi I_r) \tag{4}$$

$$I_s(t) = \sqrt{2}|I_s|\sin(2\pi ft - \frac{2\pi}{3} + \varphi I_s) \tag{5}$$

$$I_t(t) = \sqrt{2}|I_t|\sin(2\pi ft + \frac{2\pi}{3} + \varphi I_t) \tag{6}$$

In the above equations, V_r , V_s and V_t are the maximum values of the fundamental components, respectively. From these equations, it is observed that the fundamental voltage component forms a balanced three-phase system with abc sequence. Considering the above equations, it can be concluded that the neutral current is as follows:

$$I_n = i_r + i_s + i_t = 0 \tag{7}$$

As shown in equation (7), in a balanced system, no current flows through the neutral. In this case, the behavior of all loads, in any type of harmonic distortion throughout the entire period, can be expressed as a set of sinusoidal waves. However, the distortion wave by nonlinear loads, which are usually periodic and non-sinusoidal, is detected using the Fourier series and is as follows:

$$i_{r(n)} = \sum_{n=1,2,3}^{\infty} \sqrt{2} I_{rn}(\sin(\omega_n t) + \varphi_{ir(n)}) \tag{8}$$

$$i_{s(n)} = \sum_{n=1,2,3} \sqrt{2} I_{sn}(\sin(\omega_n t) - \frac{2n\pi}{3} + \varphi_{is(n)}) \tag{9}$$

$$i_{t(n)} = \sum_{n=1.2.3}^{\infty} \sqrt{2} I_{tn} (\sin(\omega_n t) + \frac{2n\pi}{3} + \varphi_{it(n)}) \quad [10]$$

where n is the number of existing harmonics, I_{rn} and I_{sn} and I_{tn} are the effective values respectively ω_n is the angular frequency, and $\varphi_{is(n)}$ is the phase shift between vs and I_{sn} . According to the aforementioned relationships, in this case, for a balanced three-phase network, the third harmonic is obtained from the following relation:

$$i_r = \sin(100\pi t) + 0.3\sin(3 * 100\pi t) \quad [11]$$

$$i_s = \sin\left(100\pi t - \frac{2\pi}{3}\right) + 0.3\sin\left(3 * 100\pi t - \frac{2 * 3\pi}{3}\right) \quad [12]$$

$$i_t = \sin\left(100\pi t + \frac{2\pi}{3}\right) + 0.3\sin\left(3 * 100\pi t + \frac{2 * 3\pi}{3}\right) \quad [13]$$

As observed from the above relations, the third harmonic voltages of the three voltages are in phase (like three single-phase systems connected together). In other words, the third multiple harmonic voltages in the three windings act from one end of the windings to the other at a specific moment in time. Note that the harmonic values are the same in all three phases. Additionally, according to equations (8-10) for the fifth harmonic, we have:

$$i_r = \sin(100\pi t) + 0.1\sin(5 * 100\pi t) \quad [14]$$

$$i_s = \sin\left(100\pi t - \frac{2\pi}{3}\right) + 0.1\sin\left(5 * 100\pi t - \frac{2 * 5\pi}{3}\right) \quad [15]$$

$$i_t = \sin\left(100\pi t + \frac{2\pi}{3}\right) + 0.1\sin\left(5 * 100\pi t + \frac{2 * 5\pi}{3}\right) \quad [16]$$

The fifth harmonic voltages have a 120-degree phase shift from each other but, contrary to the fundamental phase sequence, have an acb phase sequence, which causes braking torque in induction motors. The seventh harmonic voltages have an abc phase sequence. Also, according to equations (8-10) for the seventh harmonic, we have:

$$i_r = \sin(100\pi t) + 0.05\sin(7 * 100\pi t) \quad [17]$$

$$i_s = \sin\left(100\pi t - \frac{2\pi}{3}\right) + 0.05\sin\left(7 * 100\pi t - \frac{2 * 7\pi}{3}\right) \quad [18]$$

$$i_t = \sin\left(100\pi t + \frac{2\pi}{3}\right) + 0.05\sin\left(7 * 100\pi t + \frac{2 * 7\pi}{3}\right) \quad [19]$$

Since the third and seventh harmonic currents do not differ in amplitude and angle, both harmonic components 3 and 7 can be significant factors in the imbalance of the network.

3. CHARACTERISTICS OF HARMONIC LOADS

With advancements in technology, today's distribution networks encompass a variety of loads. However, with the progression of power electronics in power systems, we now observe highly nonlinear loads with complex structures. Examples of nonlinear loads in distribution networks include high-voltage DC systems, wind farms, photovoltaic power plants, and fluorescent lighting, all of which contain power electronic devices. Nevertheless, the main portion of these loads consists of industrial, residential, and commercial consumers. These consumers utilize 2-level or 3-level converters with diode or thyristor rectifiers, which have different switching frequencies. These are analyzed comprehensively below.

4. STUDIED NETWORK

Harmonics in the energy system have increased significantly due to the rise in nonlinear loads in recent years. Based on the discussions in previous sections, the system under study is a distribution network. For simulating the studied system, the Matlab/Simulink software has been utilized. The loads connected to the network are in several

states, such as resistive loads, resistive-capacitive loads, and resistive-inductive-capacitive loads, with the main component having the same amplitude, while the currents of other harmonics form as a function of the main components. Additionally, efforts have been made to keep the power load constant at 800 watts. The primary voltage of the transformers is 20 kV, and the secondary voltage is 400 V line-to-line, tested in various transformer vector groups. Figure 1 provides an overview of the studied network.

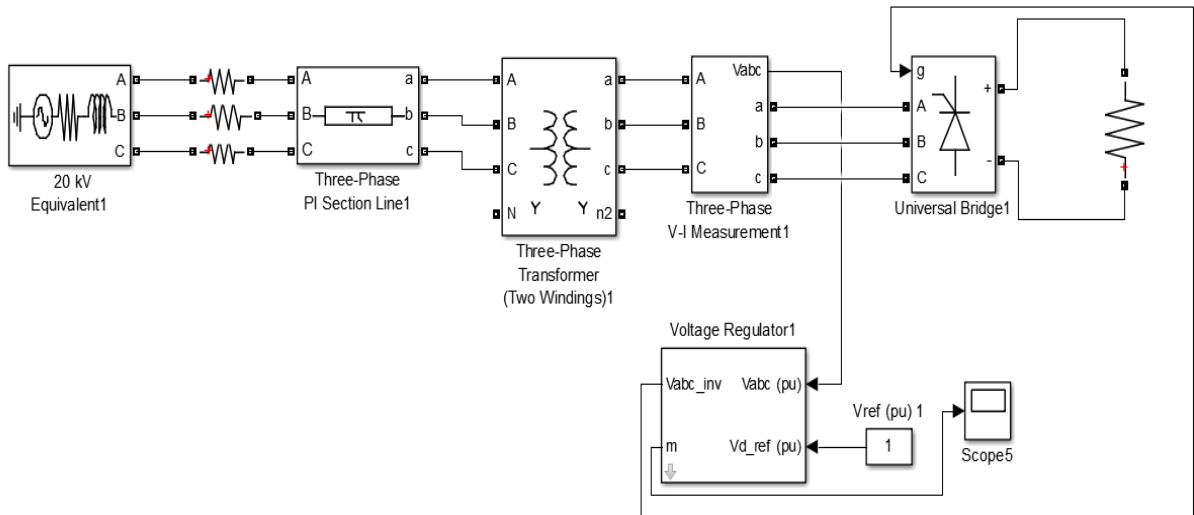


Fig.1. System Under Study for Evaluating Harmonic Effects on Distribution Transformers

The general specifications of the network transformer under study are provided in Table 1.

Table 1. Specifications of the Proposed Transformer

Specification	Values
Rated Power	630 (KVA)
Rated Frequency	50 (HZ)
Primary Voltage	20000 (V)
Secondary Voltage	400 (V)
Rated Primary Current	18.2 (A)
Rated Secondary Current	909 (A)
Primary Winding Resistance	7.549 (Ω)
Secondary Winding Resistance	0.00262 (Ω)
No-load Losses	1300 (W)
Load Losses	6500 (W)
Cooling Method	ONAN

Additionally, the thyristor firing angle is set to 90 degrees throughout the study period. Figure 1 illustrates the studied system. To investigate and analyze this system, three scenarios have been defined as follows:

1. Scenario 1: Evaluating the effects of harmonics on the transformer considering a resistive load.
2. Scenario 2: Evaluating the effects of harmonics on the transformer considering a resistive-capacitive load.
3. Scenario 3: Evaluating the effects of harmonics on the transformer considering a resistive-inductive-capacitive load.

A voltage regulator is utilized in this study to stabilize the output voltage of the transformer for feeding the thyristor firing angle.

4.1. Scenario 1: Evaluating the Effects of Harmonics on the Transformer Considering a Resistive Load (R)

In this scenario, a pure resistive load is used to investigate the behavior and effects of third, fifth, and seventh harmonics on distribution transformers. Given that a thyristor is used for AC current control, a stabilized voltage must be injected to trigger the firing angle, which is done by the voltage regulator, commonly referred to as the firing circuit. Figure 2 shows the effects of the third harmonic on the transformer with a resistive load and a 90-degree firing angle.

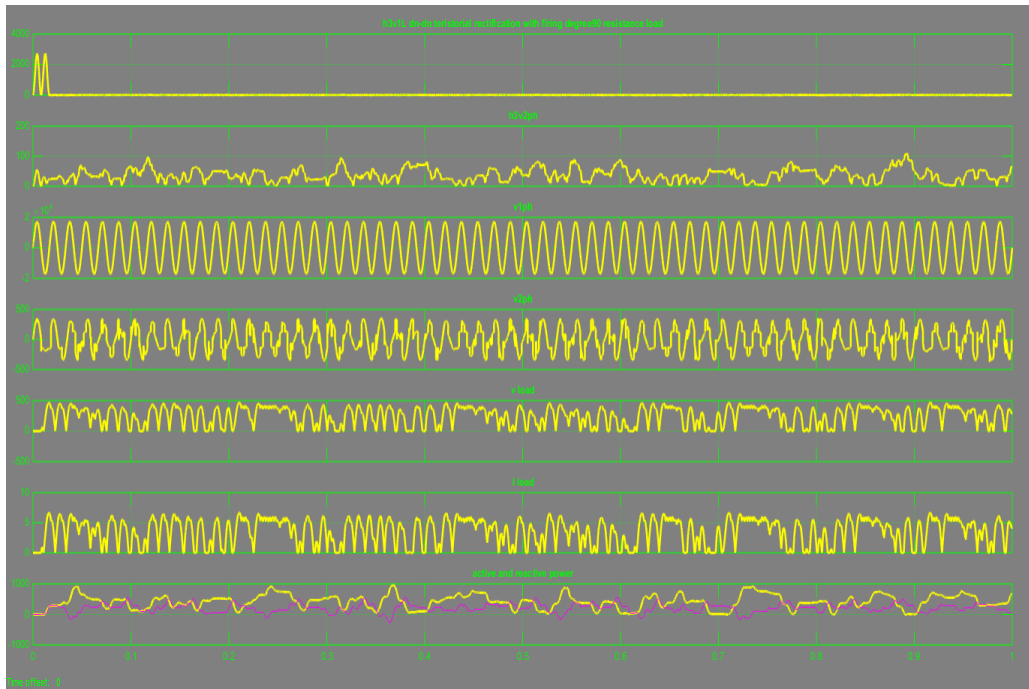


Fig.2. Effects of Third Harmonic on Transformer with Resistive Load and Firing Angle of 90 Degrees

In Figure 2, the first output pertains to the thyristor, which has managed to neutralize the harmonic load at a 90-degree firing angle and has received stabilized voltage from the voltage regulator after two cycles. The third waveform represents the voltage magnitude at the primary side of the transformer, transmitted via the transmission line. As indicated, this voltage is purely sinusoidal and free of harmonics. However, the third waveform, which shows the voltage across the output terminals of the transformer, exhibits the influence of harmonics on the output waveform. The second waveform illustrates the harmonic effects generated within the transformer on the output voltage. The fifth and sixth waveforms depict the voltage and current across the resistive load, respectively, demonstrating how harmonic effects prevent the attainment of a complete sinusoidal waveform to the resistive load. Given the use of a thyristor, it is no longer possible to maintain the power at a steady 800 watts; hence, the seventh waveform is provided to show the active and reactive power of the load. Figure 3 presents the stabilized voltage regulated by the voltage regulator. The fifth and seventh harmonic effects on the resistive load are illustrated in Figures 4 and 5, respectively.

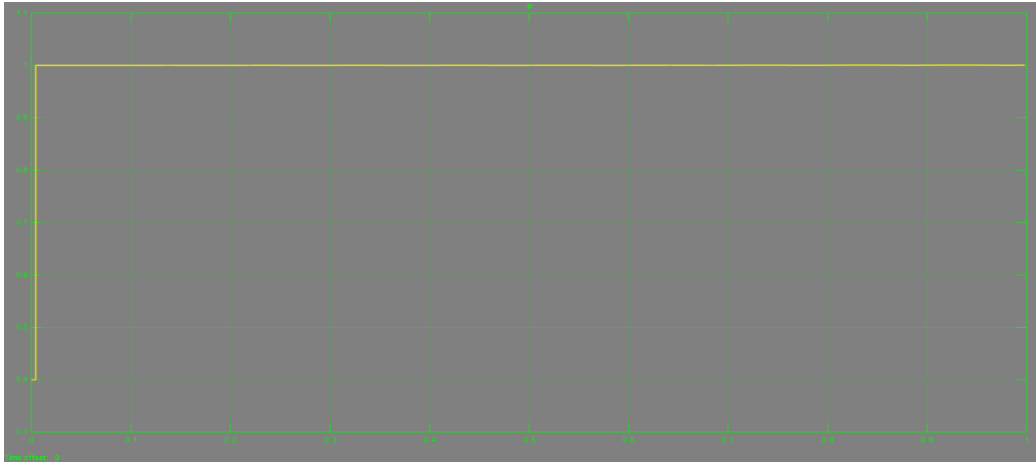


Fig.3. Stabilized Voltage by the Voltage Regulator

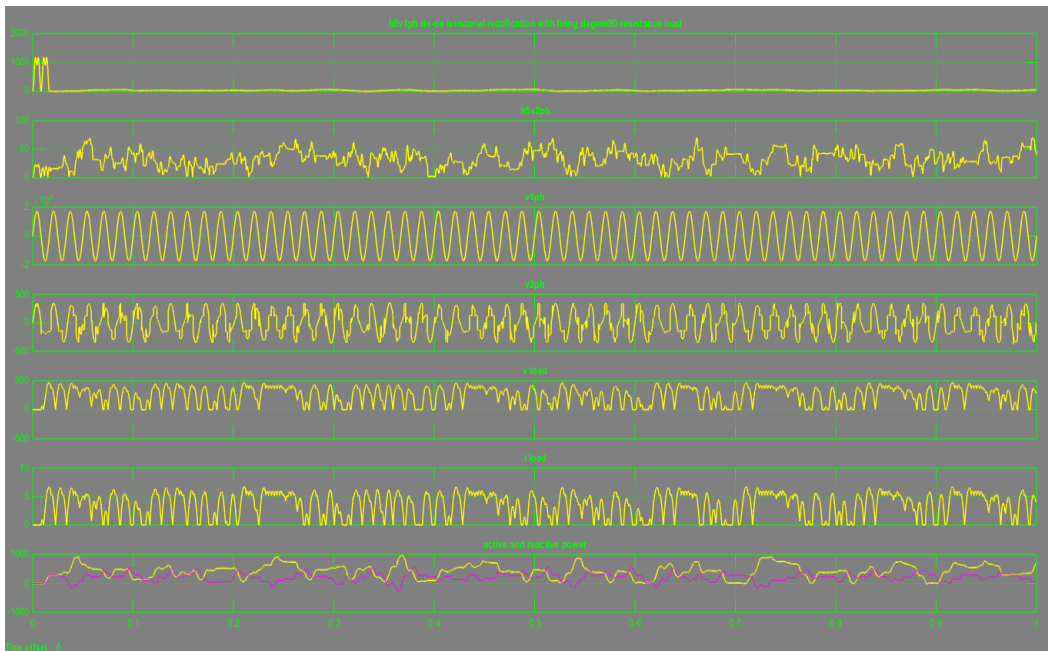


Fig.4. Effects of Fifth Harmonic on Transformer with Resistive Load and Firing Angle of 90 Degrees

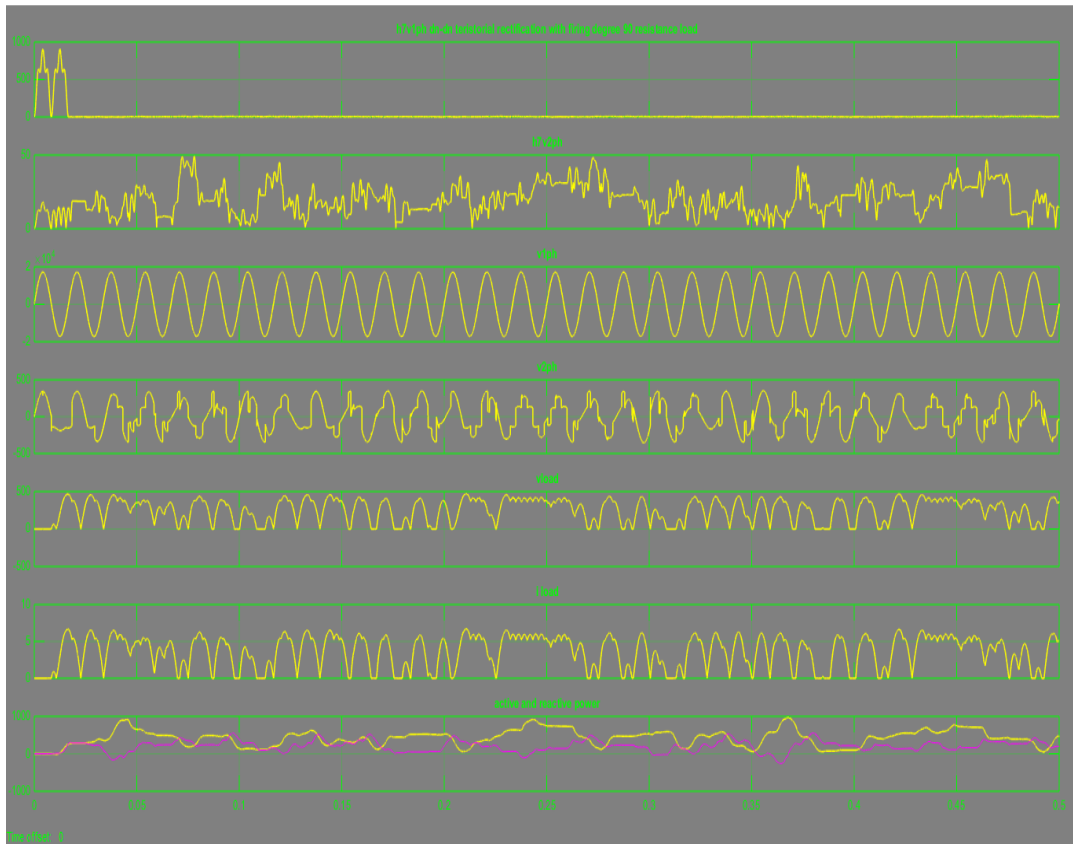


Fig.5. Effects of Seventh Harmonic on Transformer with Resistive Load and Firing Angle of 90 Degrees

4.2. Scenario 2: Examining Harmonic Effects on Transformer with Resistive-Capacitive (RC) Parallel Load

In this scenario, a resistive-capacitive load is used to analyze the behavior and effects of third, fifth, and seventh harmonics on distribution transformers. Since a thyristor is used to control the alternating current, a stabilized voltage must be injected for the firing angle trigger, achieved by the voltage regulator, also referred to as the firing circuit. The figure below shows the effects of the third harmonic on the transformer with a resistive-capacitive load and a 90-degree firing angle.

In Figure 6, the first output pertains to the thyristor, which has managed to neutralize the harmonic load at a 90-degree firing angle and has received stabilized voltage from the voltage regulator after two cycles. The third waveform represents the voltage magnitude at the primary side of the transformer, transmitted via the transmission line. As indicated, this voltage is purely sinusoidal and free of harmonics. However, the third waveform, which shows the voltage across the output terminals of the transformer, exhibits the influence of harmonics on the output waveform. The second waveform illustrates the harmonic effects generated within the transformer on the output voltage. The fifth and sixth waveforms depict the voltage and current across the resistive-capacitive load, respectively, demonstrating how harmonic effects prevent the attainment of a complete sinusoidal waveform to the resistive-capacitive load. Given the use of a thyristor, it is no longer possible to maintain the power at a steady 800 watts; hence, the seventh waveform is provided to show the active and reactive power of the load. The effects of the third harmonics are shown in Figure 6, the fifth harmonics in Figure 7, and the seventh harmonics in Figure 8 for the resistive-capacitive load.

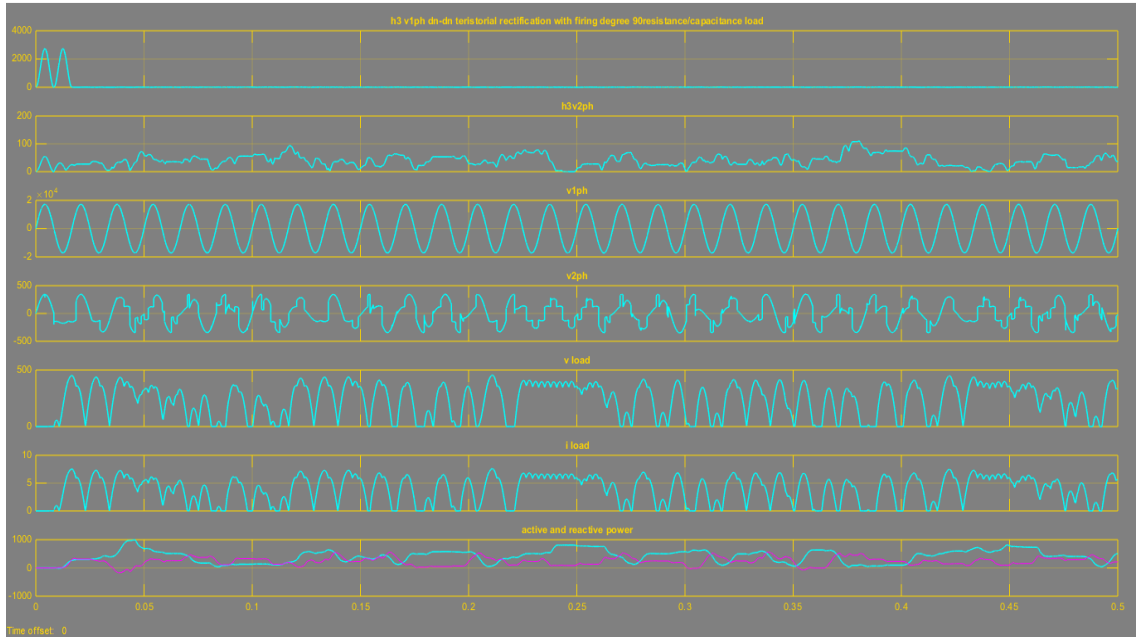


Fig.6. Effects of Third Harmonic on Transformer with Resistive-Capacitive Load and Firing Angle of 90 Degrees

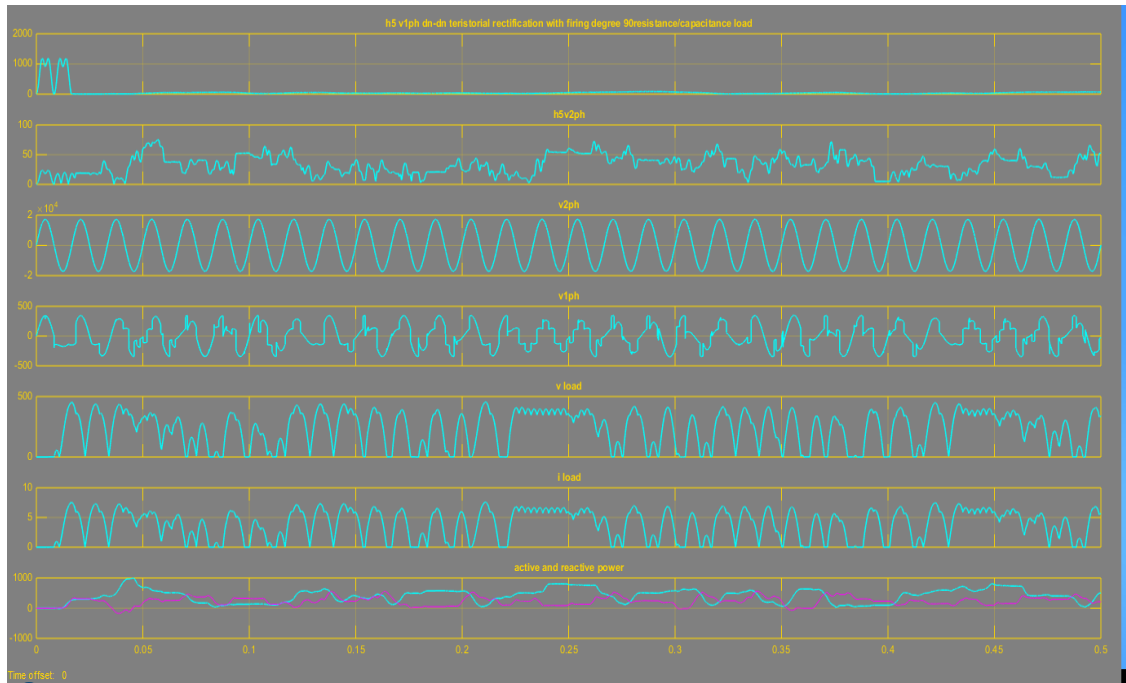


Fig.7. Effects of Fifth Harmonic on Transformer with Resistive-Capacitive Load and Firing Angle of 90 Degrees

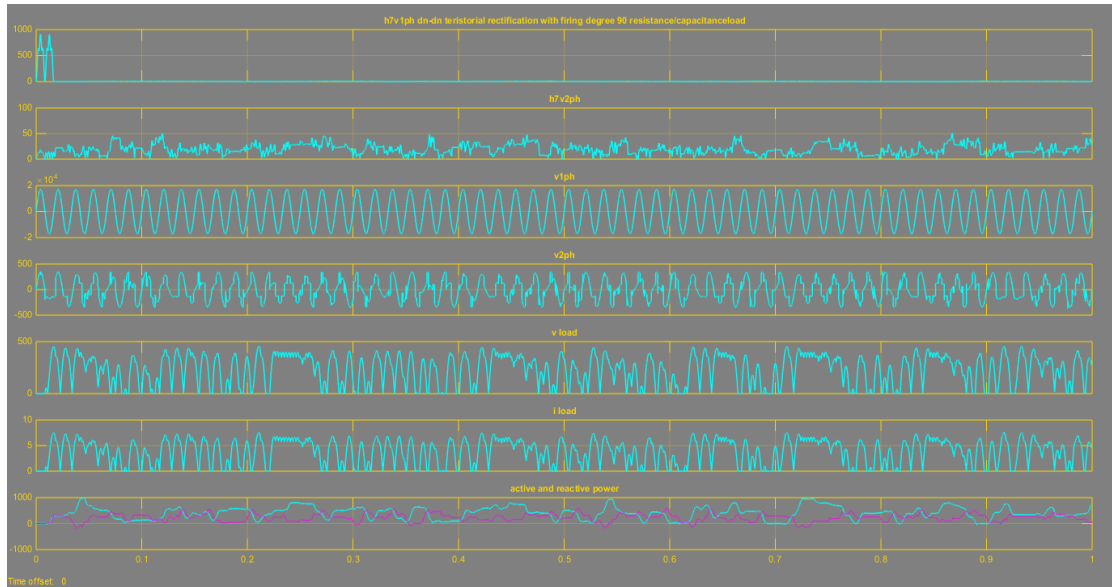


Fig.8. Effects of Seventh Harmonic on Transformer with Resistive-Capacitive Load and Firing Angle of 90 Degrees

4.3. Scenario 3: Examining Harmonic Effects on Transformer with Resistive-Inductive-Capacitive (RLC) Load

In this scenario, a resistive-inductive-capacitive load is used to analyze the behavior and effects of third, fifth, and seventh harmonics on distribution transformers. Since a thyristor is used to control the alternating current, a stabilized voltage must be injected for the firing angle trigger, achieved by the voltage regulator, also referred to as the firing circuit. Figure 9 shows the effects of the third harmonic on the transformer with a resistive-inductive-capacitive load and a 90-degree firing angle.

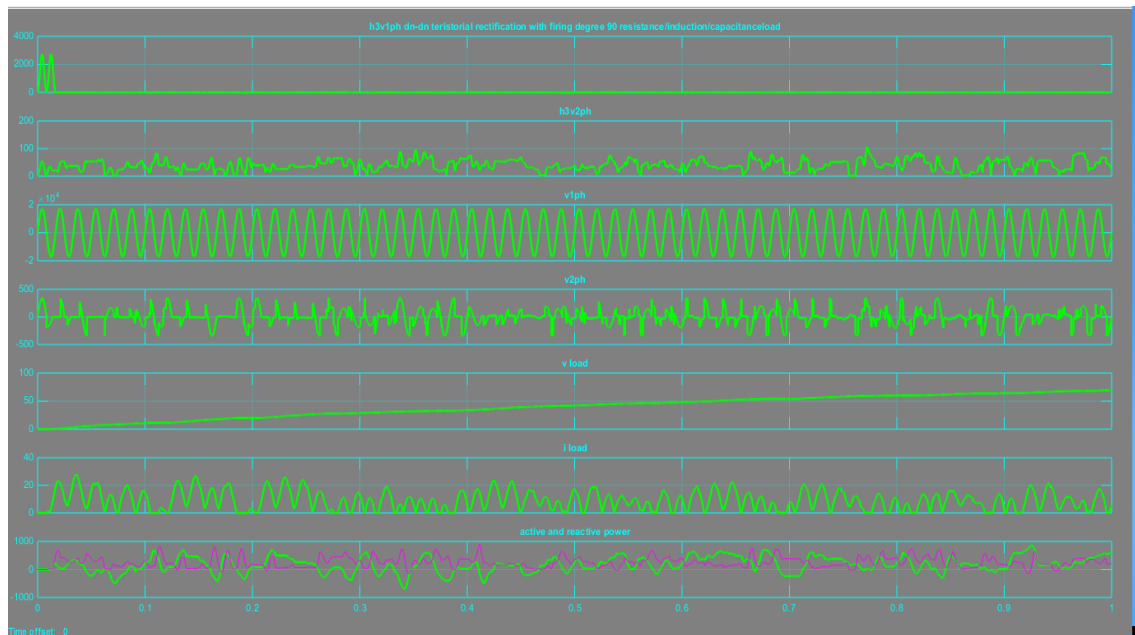


Fig.9. Effects of Third Harmonic on Transformer with Resistive-Inductive-Capacitive Load and Firing Angle of 90 Degrees

In Figure 9, the first output pertains to the thyristor, which has managed to neutralize the harmonic load at a 90-degree firing angle and has received stabilized voltage from the voltage regulator after two cycles. The third waveform represents the voltage magnitude at the primary side of the transformer, transmitted via the transmission line. As indicated, this voltage is purely sinusoidal and free of harmonics. However, the third waveform, which shows the voltage across the output terminals of the transformer, exhibits the influence of harmonics on the output waveform. The second waveform illustrates the harmonic effects generated within the transformer on the output voltage. The fifth and sixth waveforms depict the voltage and current across the resistive-inductive-capacitive load, respectively, demonstrating how harmonic effects prevent the attainment of a complete sinusoidal waveform to the resistive-inductive-capacitive load. Given the use of a thyristor, it is no longer possible to maintain the power at a steady 800 watts; hence, the seventh waveform is provided to show the active and reactive power of the load. The effects of the fifth and seventh harmonics are shown in Figures 10 and 11, respectively, for the resistive-inductive-capacitive load.

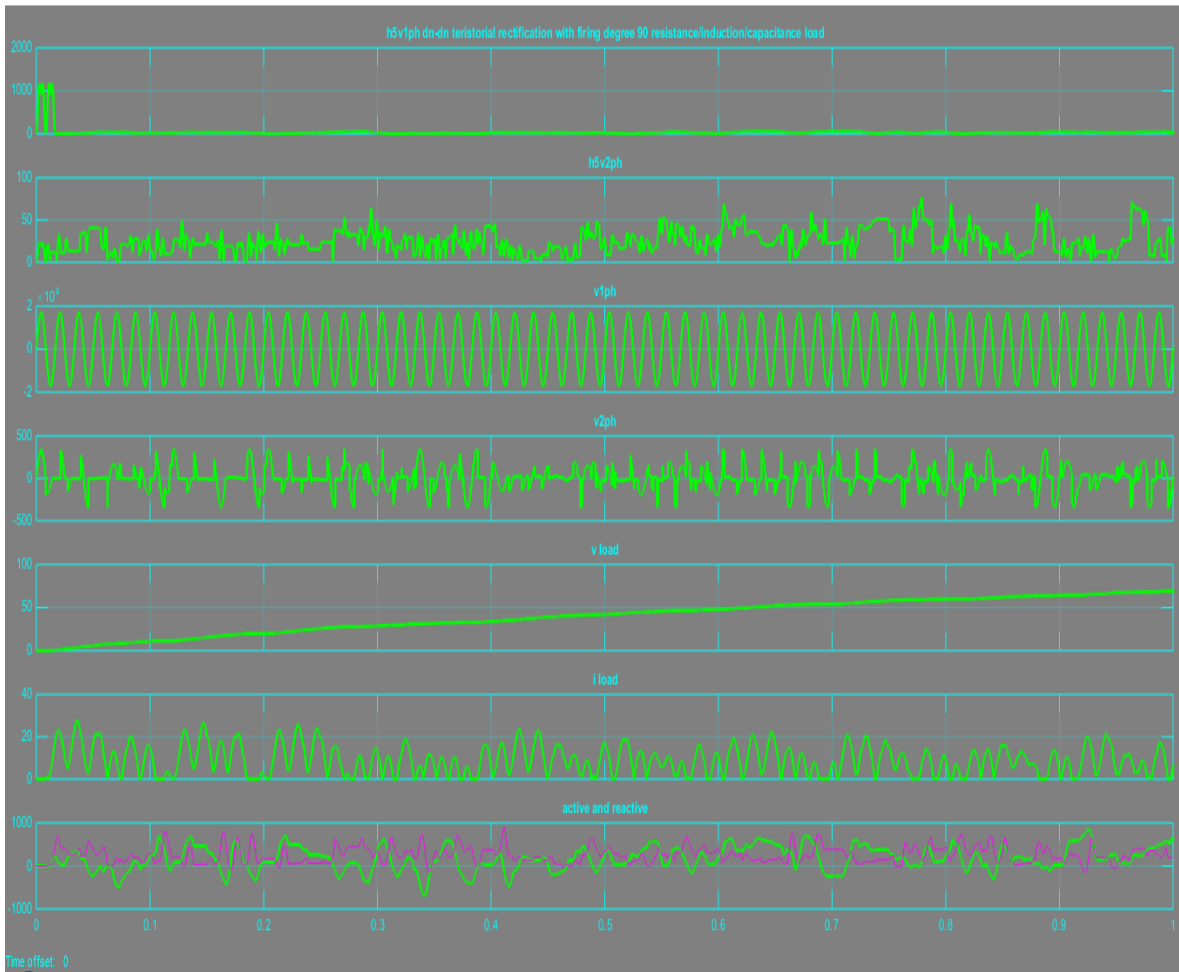


Fig.10. Effects of Fifth Harmonic on Transformer with Resistive-Inductive-Capacitive Load and Firing Angle of 90 Degrees

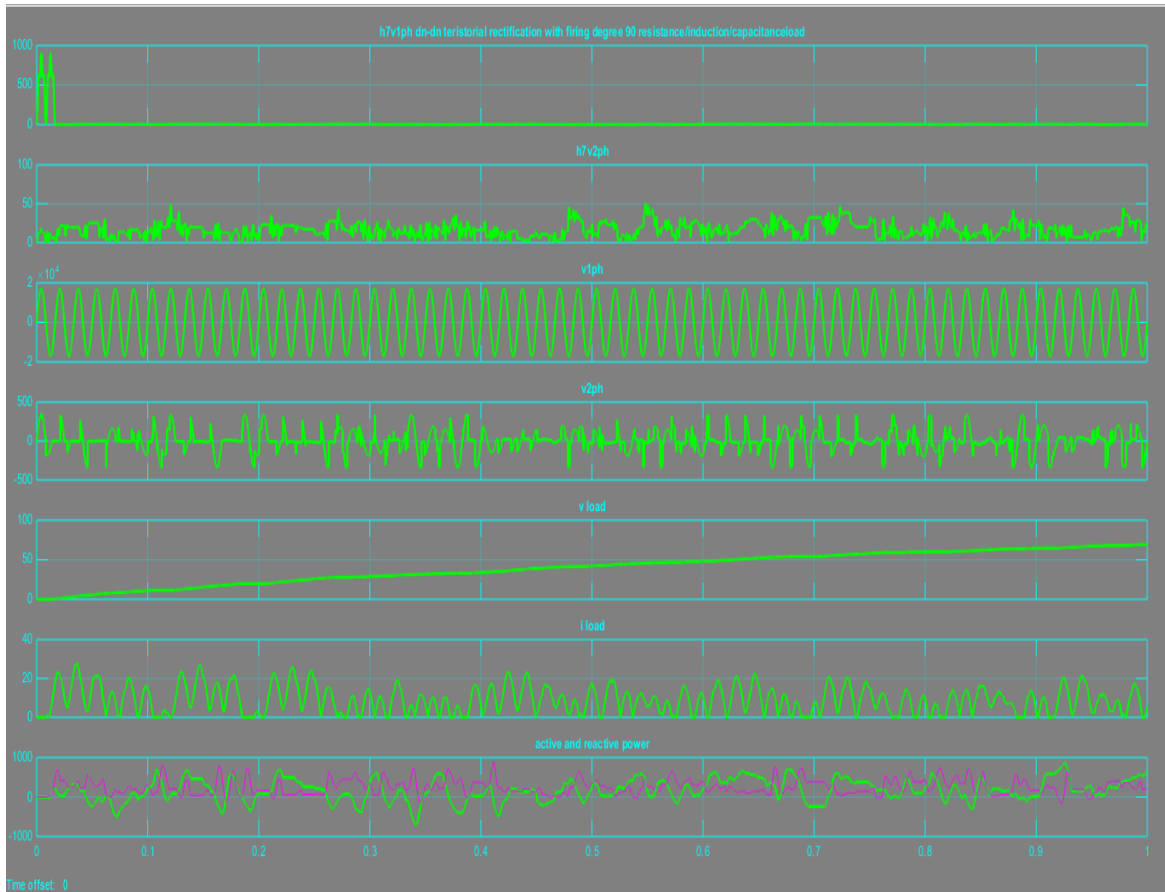


Fig.11. Effects of Seventh Harmonic on Transformer with Resistive-Inductive-Capacitive Load and Firing Angle of 90 Degrees

5. CONCLUSION

Given the rapid growth of power electronics devices and the consequent increase in the use of nonlinear loads in power systems, it is crucial to study and analyze the effects of harmonics on distribution transformers and to develop techniques to mitigate these harmonics. This study aims to examine the impact of each harmonic component on distribution transformers using Matlab/Simulink software. In this paper, we investigate the harmful effects of harmonic voltage on distribution transformers with a capacity of 630 KVA. To gain a better understanding of the issue, three scenarios were defined, considering the type of load in each scenario to examine the harmonic effects on the transformer.

The simulation results indicate that the presence of harmonic voltage in the secondary currents of the transformer is due to harmonic voltages in nonlinear loads. The defined scenarios also demonstrate that the transformer used can be loaded up to 0.79% of its nominal capacity. Furthermore, the results show that the contribution of each harmonic component depends on its amplitude and phase angle, with the impact on the fundamental frequency being significantly greater than that of other harmonic components. This is due to the asymmetry and phase difference between phases.

Under harmonic conditions, to improve the expected lifespan of the transformer, the loading on the transformer should be minimized as much as possible. Additionally, harmonic filters can be used to eliminate harmonic currents, thereby reducing harmonic losses and improving the transformer's lifespan.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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