

Analysis of the Effect of Harmonic Distortion on the Performance of a 1600 Kva Distribution Transformer in an Industrial Electrical System Using Matlab/Simulink

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KEYWORDS

*Harmonic distortion;
1600 kVA transformer;
THD-I;
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ABSTRACT – Distribution transformers are important components in industrial electrical systems because their performance is affected by power quality conditions, particularly harmonic distortion generated by nonlinear loads. This study aims to analyze the effect of harmonic distortion on the performance of a 1600 kVA distribution transformer and to compare field measurement results with simulation results using MATLAB and Simulink. Real measurements were conducted by using a Hioki PQ3198 and PQ One program on the distribution panel of the transformer. Measurement results showed THD-I values of 6.53% for phase R, 7.58% for phase S, and 7.50% for phase T, with an average apparent power of 307.1 kVA. MATLAB analysis was carried out with the variation of THD-I in the range of 0% to 20% to assess the effect on the RMS current, loading, and the copper loss index. However, Simulink analysis was performed using the nonlinear load, specifically a six-pulse diode rectifier. RMS current calculations based on fundamental current and THD yielded 462.282 A, 439.658 A, and 454.373 A for phases R, S, and T, respectively; meanwhile, the rectifier model produced a THD-I of 12.7159%, with the 5th harmonic (H5) component at 51.6665 and the 7th harmonic (H7) at 19.5684. These findings show that an increase in THD-I increases the effective current from a mathematical perspective, while a six-pulse rectifier gives rise to more distortion compared to the average case studied in practice.

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INTRODUCTION

Distribution transformers are key components in industrial electrical systems, as they step down electrical energy from distribution voltage levels to voltages suited to load requirements[1]. Industrial operating conditions for transformers can fluctuate due to varying usage of motors, inverters, variable speed drives, rectifiers, and other power electronic equipment[2]. Rectifiers can be classified as non-linear loads that are able to generate harmonics in the current[3]. Non-linear loads create non-sinusoidal currents, which result in the creation of harmonics in the system[4][5]. Harmonic components can increase RMS current and cause additional losses in conductors and transformer windings[6]. Calculations of transformer losses must account for the effects of harmonic currents[7]. Consequently, harmonic measurement and analysis become very important in order to know the true scenario and possible effects on the performance of the transformer. These same issues are also applicable to electrical systems at sea, where transformers provide power to electric motors, drives, rectifiers, and other power electronics that are used aboard vessels and ports. These loads are non-linear and can produce harmonic operation[8].

Subject matter of this study is an ABB distribution transformer that has a capacity of 1600 KVA and operates in three phases. The transformer features a primary voltage of 3.3 kV, a secondary voltage of 400 V, a frequency of 50 Hz, an impedance of 5.9%, a Dyn5 vector group, and an ONAN cooling system. The transformer's secondary-side rated current of approximately 2309 A serves as the reference for load evaluation. The measurements for power quality were done by Hioki PQ3198 at the transformer distribution panel, and the following parameters were measured: Voltage, Current, Frequency, Power Factor, Power, Voltage THD, and Current THD[9]. This information was used in developing a mathematical model of simulating to identify the relationship between harmonic distortion and the operation of the transformer. Other examples of the same transformer connection can be found in marine electrical systems, where there is a need for a dependable distribution of electrical energy in propulsion systems and auxiliary machinery. Therefore, power quality evaluation is also applicable for marine engineering when non-linear loads operate continuously[10].

Research on transformer harmonics indicates that the impact of harmonic currents extends beyond increased RMS current; it is also linked to increased additional losses and hotspot temperatures. Harmonics in voltage and

current have potential to cause damage to the electrical system and electrical devices. Effect of harmonics on electrical devices involves effect on capacitors, transformers, and three phase motors. Capacitors are affected by harmonics because of the decrease in capacitive reactance at high frequencies[11]. Previous literature reveals that there is an effect of current THD on the temperature of transformer hotspot when the harmonic component is increasing[12][13]. Calculation using IEEE 519 method also demonstrates that transformer capabilities with non-sinusoidal loading must take into account load losses and harmonic currents[14][15]. The loss in the transformer due to non-linear load affects insulation temperature, thus causing a reduction in the lifetime left. Non-linear loads will require transformer[16].

Therefore, combining direct field measurements, MATLAB analysis, and Simulink modeling provides a more comprehensive approach to evaluating harmonic distortion in distribution transformers. Direct field measurement using a power quality analyzer has the advantage of providing actual operating conditions and real harmonic characteristics of the transformer under industrial loads. It can directly capture parameters such as RMS current, voltage, power, power factor, and THD-I [17]. However, field measurements are generally limited to the operating conditions and load characteristics present during the measurement period, making it difficult to evaluate transformer behavior under harmonic conditions that have not occurred in the field. MATLAB provides greater flexibility for numerical analysis because different THD-I conditions can be mathematically varied to evaluate their effects on RMS current, transformer loading, and relative loss indices. Nevertheless, MATLAB-based calculations depend on mathematical assumptions and input parameters and therefore may not fully represent the nonlinear waveform characteristics generated by actual power electronic loads.

However, the accuracy of the Simulink results depends on the accuracy of the model parameters, component configuration, and simulation assumptions. Thus, direct measurement provides practical validation under actual operating conditions, MATLAB enables controlled numerical evaluation of different THD-I scenarios, and Simulink provides detailed modeling of harmonic generation from nonlinear loads. The combination of these three approaches allows the measured harmonic conditions to be validated through numerical analysis and further investigated using a nonlinear load model, providing a more comprehensive assessment of harmonic distortion in the 1600 kVA distribution transformer. The objectives of this research a MATLAB-based electrical analysis has also been applied to maritime electrical systems to evaluate load distribution and operating conditions on electric ships[18]. The evaluation of electrical loads and power distribution is also important in marine electrical systems, where generator loading and electrical energy efficiency directly affect vessel operation[19]. Similarly, the above-mentioned consideration is also relevant to the case of electrical power system on board ships where reliable power distribution is required for various electrical loads[8]. The use of power electronic equipment and drives in such systems can also introduce harmonic distortion.

The objectives of this research are to investigate the THD-I characteristics of a 1600 kVA distribution transformer through power quality analysis, evaluate the effects of varying THD-I values on RMS current and relative loss indices using MATLAB, and investigate the harmonic characteristics produced by a six-pulse rectifier load using Simulink. The measurement, MATLAB, and Simulink approaches are used as complementary methods to examine harmonic distortion from different perspectives. Direct measurement provides actual operating data from the transformer, MATLAB enables controlled numerical evaluation of different THD-I conditions, and Simulink enables investigation of harmonic characteristics generated by a nonlinear load. Consequently, this research integrates Power Quality Analyzer measurements with MATLAB and Simulink analyses to assess the current distortion characteristics of the 1600 kVA distribution transformer and to identify the relationship between measured, calculated, and simulated harmonic characteristics.

METHODS

Research Flowchart

An algorithm for research was generated to relate field measurements with MATLAB analysis and Simulink modeling. Field data was gathered by direct measurement through the use of Hioki PQ3198 on a 1600 kVA distribution transformer, then analyzed with the PQ One software. This data consisted of parameters which include voltage, current, THD-I, THD-V, apparent power, and loading. These parameters served as the basis for MATLAB calculations to analyze RMS current and the relative loss index in relation to THD-I variations, while Simulink was used to analyze harmonic characteristics under a nonlinear load scenario involving a six-pulse diode rectifier. Thus, the PQ One data represent actual measured conditions, whereas MATLAB and Simulink serve as analytical and simulation tools to evaluate the system's response to varying levels of harmonic distortion.

The research process began with the collection of transformer nameplate data and power quality measurement data. This data was then processed to obtain average voltage, fundamental current, RMS current, THD-I, THD-V, power factor, and apparent power values[20]. Subsequently, mathematical calculations were performed using MATLAB to determine the relationship of THD with RMS current, loading, and the relative loss index

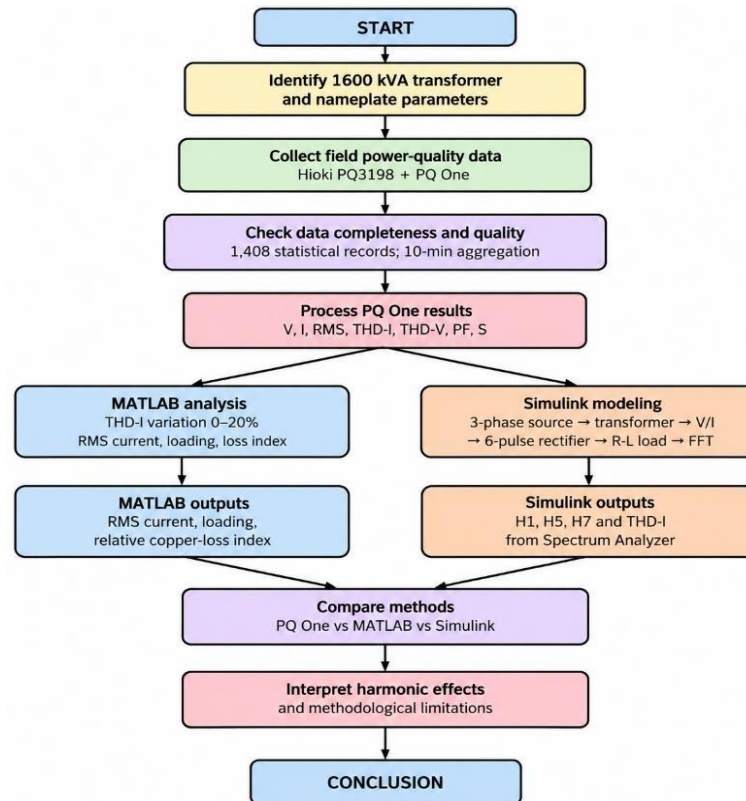


Figure 1. Research methodology flowchart

A Simulink model was then employed to represent the transformer and a nonlinear load in the form of a six-pulse diode rectifier. The PQ One measurement results served to represent actual operating conditions, while the Simulink model was used to analyze the system's response to the nonlinear load scenario involving the six-pulse diode rectifier. A descriptive comparison of the two sets of results was conducted based on the THD-I characteristics and harmonic components obtained from each method[21].

Distribution Transformer

Distribution transformers operate on the principle of electromagnetic induction to transfer electrical energy from the primary winding to the secondary winding. Under ideal conditions, the relationship between voltage and current is determined by the ratio of the number of primary and secondary turns. In real-world conditions, however, transformers possess internal impedance and experience losses arising from the windings and core, as well as additional losses caused by harmonic currents. Nonlinear loads cause the current waveform to deviate from a sinusoidal shape, resulting in an RMS value that exceeds that of the fundamental component. These conditions become critical when the transformer operates at high loading levels or is subjected to continuous harmonic currents.

The specifications of the transformer used in this study are summarized in Table 1.

Table 1. Distribution Transformer Specifications

Parameter	Value
Manufacturer	ABB
Rated Capacity	1600 kVA
Primary Voltage	3.3 kV
Secondary Voltage	400 V
Frequency	50 Hz
Primary Current	280 A
Secondary Current	2309 A
Impedance	5.9%
Vector Group	Dyn5
Cooling Method	ONAN
Temperature Rise	60/65 K

Transformer specification data serve as key parameters for load analysis and system modeling. The distribution transformer used in this study is an ABB transformer with a rated capacity of 1600 kVA, a primary voltage of 3.3 kV, and a secondary voltage of 400 V. The transformer operates at a frequency of 50 Hz and has rated primary and secondary currents of 280 A and 2309 A, respectively. The transformer has an impedance of 5.9% and uses the Dyn5 vector group, with ONAN (Oil Natural Air Natural) cooling. The temperature rise is specified as 60/65 K, while the rated power factor is not specified on the available nameplate data[22][23]. These parameters are used as the basis for calculating transformer loading and modeling the electrical system, and are subsequently combined with power quality measurement results for further analysis[24].

Harmonic Distortion

Harmonic distortion is a condition in which an electrical waveform contains frequency components that are multiples of the fundamental frequency. In a 50 Hz system, the fifth-order harmonic has a frequency of approximately 250 Hz, while the seventh-order harmonic has a frequency of approximately 350 Hz. The magnitude of current distortion can be expressed using Total Harmonic Distortion of Current, or THD-I. Mathematically, THD-I represents the ratio of the RMS value of all harmonic components to the fundamental component[25]. The THD-I equation can be written as follows.

$$THD_I = \sqrt{\frac{I_2^2 + I_3^2 + \dots + I_n^2}{I_1^2}} \times 100\% \quad (1)$$

where I_1 is the fundamental current and I_n is the n th order harmonic current. The total RMS current can be calculated based on the fundamental component and THD using the equation:

$$I_{RMS} = I_1 \sqrt{1 + THD_I^2} \quad (2)$$

The THD-I value must be expressed as a decimal when substituted into the equation. This relationship indicates that an increase in THD causes a non-linear rise in RMS current[26]. This increase can subsequently affect transformer loading and loss components that depend on the square of the current[12].

Simulink System Model Diagram

In this model, a three-phase source represents the transformer's primary side. The transformer is modeled with a capacity of 1600 kVA and a voltage rating of 3.3 kV/400 V, in accordance with its nameplate data. Voltage and current measurement blocks are connected to the transformer's secondary side before the signal enters a six-pulse diode rectifier. The secondary-side current is then fed into a PS-Simulink Converter block and a Spectrum Analyzer to obtain the harmonic spectrum. Fast Fourier Transform (FFT) analysis is employed to examine the frequency spectrum of the sinusoidal signal; specifically, FFT is used to identify harmonic components based on the signal's frequency spectrum[27]. This configuration enables direct observation of the impact of nonlinear loads on the current flowing through the transformer. The simulation model comprises a three-phase voltage source, a circuit breaker, a transformer, voltage and current measurement units, and a nonlinear load consisting of a six-pulse rectifier connected to an R-L load on the DC side. A six-pulse rectifier was selected as the equivalent model for the nonlinear load because its configuration produces non-sinusoidal input current and exhibits dominant harmonic characteristics at orders harmonics ($h = 6k \pm 1$)[27] such as the 5th and 7th harmonics which align with the requirements for analyzing current harmonic distortion in three-phase systems. The current signal on the transformer side is subsequently used to derive the harmonic spectrum and THD-I value through frequency-domain analysis. The use of a six-pulse rectifier in the simulation is not intended to directly represent every nonlinear load found in industrial systems, but rather serves as an equivalent model to represent nonlinear loading characteristics. Model validation was performed by comparing the harmonic parameters obtained from the simulation with measurement results obtained using a Hioki PQ3198.

The following is the system diagram used as the basis for the Simulink model.

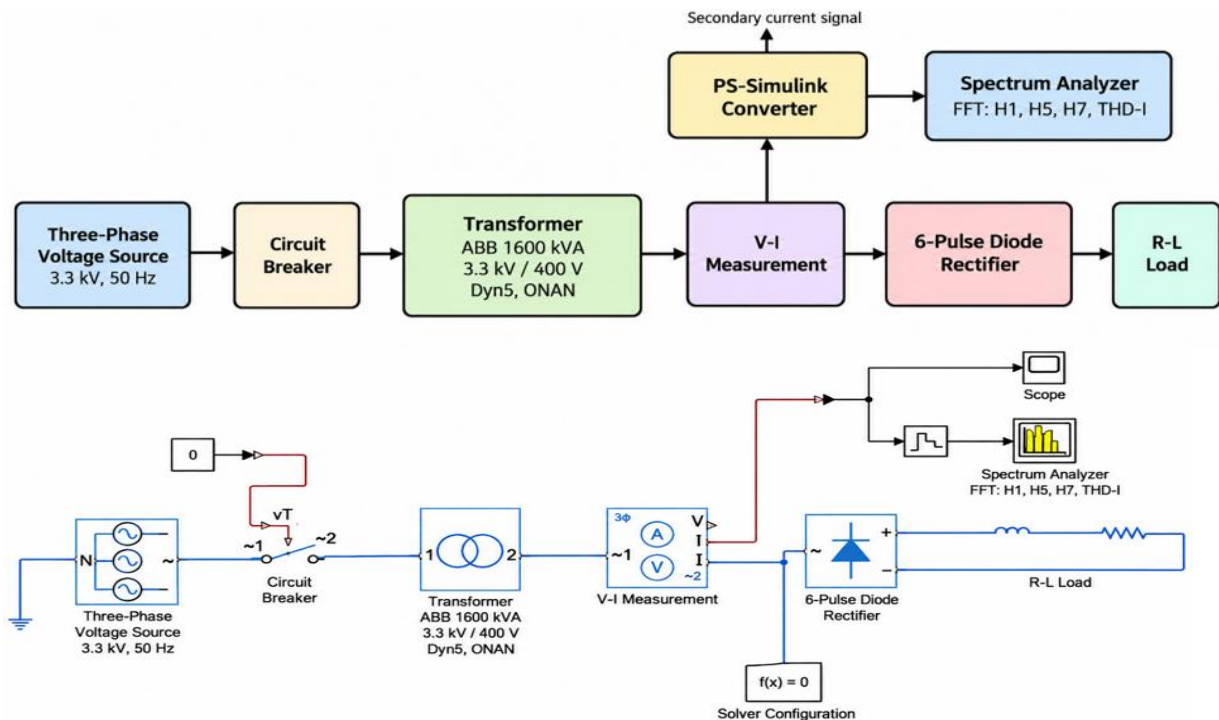


Figure 2. Diagram of the 1600 kVA transformer system model with a nonlinear load.

PQ One Measurement Data

Primary research data were obtained by measuring power quality at the distribution panel of the 1600 kVA transformer using a Hioki PQ3198 Power Quality Analyzer. Voltage measurements were connected to the three-phase secondary-side system, while current measurements were performed on phases R, S, and T using current probes, with the measurement configuration maintained consistently throughout the measurement period. Measurements were conducted from February 13, 2026, to February 23, 2026, yielding 1,408 statistical data records. statistical data records processed using PQ One software according to its configured recording and statistical aggregation settings. The analyzed parameters included voltage, fundamental current, RMS current, frequency, power factor, apparent power, THD-V, and THD-I for each phase. All valid statistical records were included in the analysis; incomplete or invalid records were excluded, while valid high or low values were retained because they represented actual variations in the transformer's operating conditions. The resulting average values were used to represent the actual operating condition of the transformer and subsequently served as the basis for MATLAB calculations and comparison with the Simulink simulation results.

Table 2. Average Measurement Results of PQ One

Parameter	Phase R	Phase S	Phase T
Average Voltage (V)	397.42	397.06	396.00
Fundamental Current (A)	461.3	438.4	453.1
RMS Current (A)	460.8	439.3	454.1
THD-I (%)	6.53	7.58	7.50
Power Factor	0.8412	0.9456	0.9706
Average Apparent Power (kVA)	104.4	99.7	103.0

Measurement results indicate that the inter-phase voltage is very close to the nominal value of 400 V. The average RMS current ranges from 439.3 A to 460.8 A, remaining well below the secondary nominal current of 2309 A. The highest THD-I occurred in phase S at 7.58%, while phase R exhibited the lowest value at 6.53%. These THD-I values indicate a measurable harmonic content in the system current. These measurement results were subsequently used to represent actual conditions in the MATLAB mathematical modeling.

Fast Fourier Transform (FFT) Analysis

FFT analysis is used to convert a time-domain current signal into a frequency spectrum representation. This method allows fundamental and harmonic components to be identified based on their respective frequencies.

Mathematically, the discrete Fourier transform can be expressed as:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N} \quad (3)$$

where $x(n)$ is the time-domain signal, $X(k)$ is the spectral component, N is the number of samples, and k is the frequency index. In Simulink, this process is represented by the Spectrum Analyzer, which displays the fundamental and harmonic components based on the spectrum analysis results. For a system with a fundamental frequency of approximately 50 Hz, the fifth-order harmonic lies around:

$$f_5 = 5 \times 50 = 250 \text{ Hz} \quad (4)$$

while the seventh-order harmonic is located at:

$$f_7 = 7 \times 50 = 350 \text{ Hz} \quad (5)$$

The harmonic characteristics of a six-pulse rectifier theoretically follow a pattern. $h = 6k \pm 1$. Consequently, the appearance of 5th-order (H5) and 7th-order (H7) harmonic components in the simulation results aligns with the harmonic characteristics of a six-pulse rectifier. In a system with a fundamental frequency of 50 Hz, H5 and H7 occur at 250 Hz and 350 Hz, respectively. These components were identified using the Fast Fourier Transform (FFT) by converting the current signal from the time domain to the frequency domain. The resulting FFT spectrum enables the identification of the fundamental frequency and harmonic components, which are subsequently used to evaluate THD-I. FFT-based analysis is appropriate for this study as it allows for the quantitative observation of current harmonic spectrum characteristics prior to comparison with measurement results obtained using the Hioki PQ3198[23].

RESULTS AND DISCUSSION

Effect of THD-I on RMS Current

The MATLAB calculation results indicate that the RMS current increases as THD-I rises. At a THD-I of 0%, the RMS current equals the fundamental current because no harmonic components are present. At a THD-I of 25%, the RMS current becomes approximately 1.0308 times the fundamental value. This relationship is nonlinear because THD-I appears as a squared term in the RMS current equation. These results demonstrate that an increase in harmonic distortion mathematically increases the effective current component flowing through the transformer.

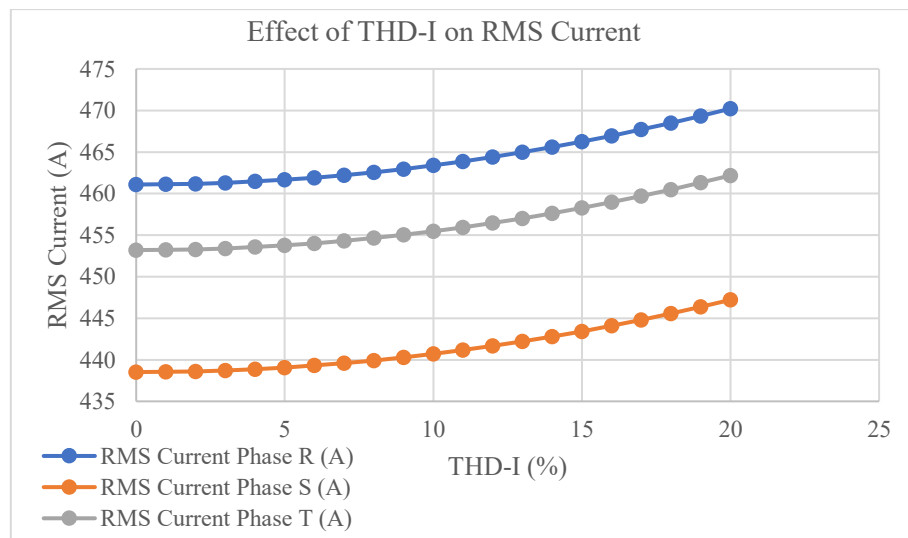


Figure 3. Effect of THD-I on RMS current (MATLAB results).

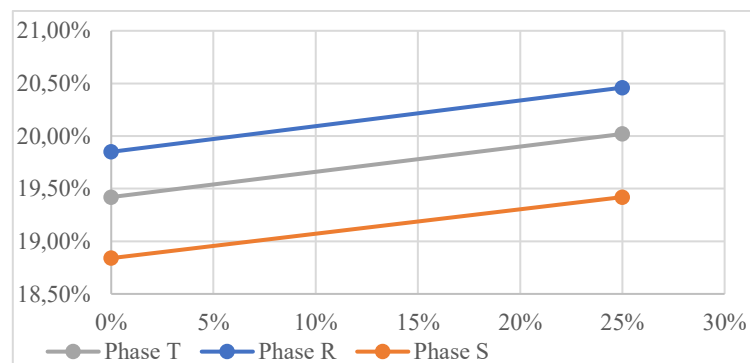
Table 3. Results of THD-I Variation vs. RMS Current

THD-I (%)	R (A)	S (A)	T (A)
0	461,300	438,400	453,100
5	461,876	438,948	453,666
6,53	462,282	439,334	454,065
7,50	462,596	439,631	454,373
7,58	462,623	439,658	454,400
10	463,601	440,587	455,360
15	466,461	443,305	458,169
20	470,436	447,082	462,073

With an actual THD of 6.53% on phase R, the RMS current derived from the model reached approximately 462.282 A. For phase S, with a THD of 7.58%, the RMS current was approximately 439.658 A. For phase T, with a THD of 7.50%, the RMS current reached approximately 454.373 A [28] This increase indicates that harmonic components contribute to the effective current, even though the rise is relatively small within the range of the actual THD values. These results serve as a basis for evaluating transformer loading under conditions of higher harmonic levels.

The Effect of THD-I on Transformer Loading

Analysis results indicate that the loading of the 1600 kVA transformer under the observed operating conditions is approximately 19.19% of its nominal capacity, meaning the transformer retains a substantial capacity margin. An average THD-I value of 7.20% indicates the presence of harmonic content in the load current flowing through the transformer. Increases in THD-I result in a gradual rise in RMS current: specifically, an increase of approximately 0.125% at 5% THD-I, 0.26% at 7%, 0.50% at 10%, 1.12% at 15%, and 1.98% at 20%. These findings demonstrate that higher harmonic content leads to a greater effective current load on the transformer, thereby increasing effective loading and conductor losses [29]. Consequently, even though the transformer's average loading level remains relatively low, the rise in THD-I warrants attention, as it can elevate the RMS current and impose additional thermal stress on the transformer.

**Figure 4.** Effect of THD-I on transformer loading.

As can be observed from the results of the analysis, an increment in THD-I will cause an increment in RMS current in each phase of the transformer. Phase R experiences an increment in RMS current as THD-I is increased from 0% to 20%, while Phases S and T experience the same trend. For the level of THD-I at about 7%, which is near to the actual average value of 7.20%, the rise in the RMS current is quite moderate; therefore, its effect on transformer loading is insignificant. The reason for this is that the basic current used during the process of analysis is significantly lower than the secondary rated current of the transformer, which is 2309A. This means that when the transformer is under lower loads, the effect of THD-I on the percentage load of the transformer is relatively low, although the increase in harmonics should not be overlooked.

The Effect of THD-I on Transformer Loading Copper Loss Increase Index

The effect of harmonics on copper losses can be analyzed simply based on the relationship between losses and

the square of the current. Since the transformer winding resistance value is not available in the research data, the losses are not calculated in watts. In its place, is an index that signifies the increase in copper losses due to the presence of harmonics. This index is calculated using the equation, which is mathematically equivalent to. The index is used as an indicator of trends and should not be interpreted as the absolute absolute loss value of the transformer

$$Loss_{index} = \frac{I_{RMS}^2 - I_1^2}{I_1^2} \times 100\% \quad (6)$$

or

$$Loss_{index} = THD_I^2 \times 100\% \quad (7)$$

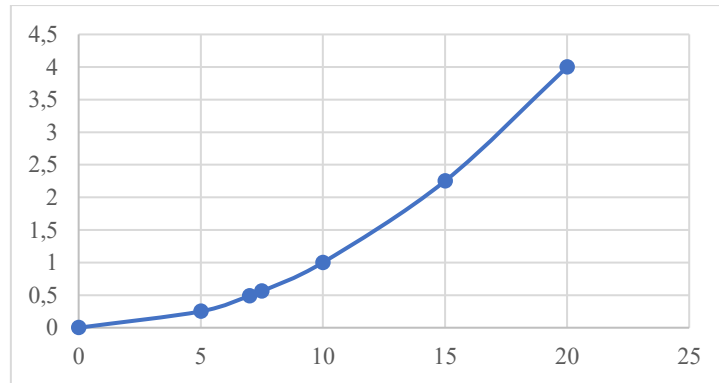


Figure 5. Relationship between THD-I and the relative copper loss increase index.

Table 4. Relative Loss Increase Index

THD-I (%)	Loss Index (%)
0	0
5	0,25
7	0,49
7,5	0,56
10	1
15	2,25
20	4

The analysis results indicate that an increase in THD-I drives a rise in the relative copper loss index of the transformer. While the measured THD-I was 7.20%, the 0–20% THD-I range served as the analysis scenario to evaluate the trend of the relative copper loss index. At a THD-I of 5%, the loss index rose to 0.25%, whereas at 10% THD-I, it reached 1.00%. When THD-I increased to 15%, the loss index reached 2.25%, and at 20% THD-I, the value climbed to 4.00%. This relationship demonstrates that the rise in the loss index follows a quadratic pattern relative to THD-I, meaning that greater distortion results in a more significant increase in losses. These findings indicate that, although the actual average THD-I of 7.20% results in a low relative loss index, the increase in harmonic content under higher loading conditions still warrants attention when evaluating transformer performance

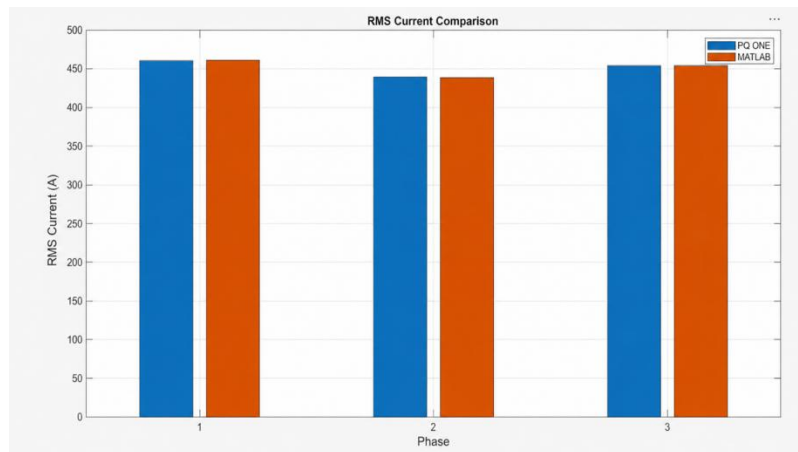
Comparison of MATLAB RMS Current Calculations with PQ One Data

A comparison was conducted using measured fundamental current and THD-I values for each phase as parameters for MATLAB calculations. The RMS current was calculated based on the relationship between the fundamental current and THD-I, and the results were compared against the average RMS current values recorded by the PQ One device. The calculations yielded RMS currents of 462.282 A for phase R, 439.658 A for phase S, and 454.373 A for phase T. The average absolute difference relative to the PQ One data was 0.154%, with phase-specific differences of 0.322% for R, 0.081% for S, and 0.060% for T. These discrepancies may be attributed to the rounding of statistical values, the use of separate average parameter values, and differences between the processing of average values and calculations derived from average parameters.

Table 5. Comparison of PQ One and MATLAB Results

Phase	Measured THD-I (%)	PQ One RMS Current (A)	MATLAB RMS Current (A)	Relative Difference (%)
R	6.53	460.8	462.282	0.322
S	7.58	439.3	439.658	0.081
T	7.5	454.1	454.373	0.06
Average	—	—	—	0.154

Table 5 shows that the RMS current values calculated using MATLAB closely match the measurements obtained from the PQ One device across all three phases. The MATLAB-calculated RMS currents were 462.282 A for phase R, 439.658 A for phase S, and 454.373 A for phase T, compared to the PQ One readings of 460.800 A, 439.300 A, and 454.100 A, respectively. The relative differences were 0.322% for phase R, 0.081% for phase S, and 0.060% for phase T, resulting in an average difference of only 0.154%. These results demonstrate that the MATLAB calculations accurately represent the RMS current values derived from the PQ One data with minimal relative discrepancy.

**Figure 6.** Comparison of RMS current from PQ One and MATLAB measurements.

The largest relative difference occurred in phase R at 0.322%, while phases S and T showed differences of 0.081% and 0.060%, respectively. The average relative difference of 0.154% indicates that the RMS current values calculated using the fundamental current and measured THD closely align with the RMS data recorded in PQ One. These discrepancies may be attributed to the rounding of statistical values and the use of average values as calculation parameters. These results serve as a comparison against calculations based on measurement data rather than as an independent validation of the MATLAB model.

FFT Spectrum Analyzer Analysis Results

In addition to the MATLAB mathematical model, Simulink was used to represent the nonlinear load conditions of the 1600 kVA distribution transformer.

Table 6. Spectrum Analyzer Results

Component	Frequency (Hz)	RMS
H1	50,3540	441,4513
H5	250,2441	51,6665
H7	349,4263	19,5684
THD-I	—	12,7159%

The model consists of a three-phase source, transformer, voltage and current measurements, a six-pulse

rectifier, and an R-L load. FFT analysis was performed using the Spectrum Analyzer to identify the fundamental and harmonic components [30]. fundamental component (H1) occurred at 50.3540 Hz with an RMS value of 441.4513, while H5 and H7 occurred at 250.2441 Hz and 349.4263 Hz with RMS values of 51.6665 and 19.5684, respectively. The simulation produced a THD-I of 12.7159%, confirming the model's ability to represent current distortion caused by nonlinear loads.[31].

The THD value can be verified from the harmonic components present:

$$THD_I = \frac{\sqrt{H_5^2 + H_7^2}}{H_1} \times 100\% \quad (8)$$

$$THD_I = \frac{\sqrt{(51,6665)^2 + (19,5684)^2}}{441,4513} \times 100\% \quad (9)$$

$$\boxed{THD_I \approx 12,72\%}$$

The current harmonic spectrum obtained from a MATLAB/Simulink simulation using a 6-pulse rectifier. The simulation results indicate a fundamental component (H1) of 441.4513 A rms, while the 5th and 7th-order harmonic components are 51.6665 Vrms and 19.5684 Vrms, respectively. Based on these harmonic components, a THD value of 12.7159% was obtained, indicating current distortion caused by the nonlinear load characteristics of the 6-pulse rectifier. The dominance of the 5th and 7th-order harmonics aligns with the general characteristics of 6-pulse rectifiers, which generate characteristic harmonics at orders $orde\ h = 6k \pm 1$. These simulation results subsequently serve as a basis for comparing the harmonic characteristics derived from the model with measurement data obtained using a Hioki PQ3198 in an industrial electrical system.

Comparison Of PQ One And Simulink Results

A comparison between the PQ One results and the Simulink simulation was conducted to examine the differences in harmonic characteristics between actual operating conditions and a nonlinear load scenario. PQ One measurements showed an average THD-I of 7.20%, whereas the Simulink simulation using a six-pulse diode rectifier yielded a THD-I of 12.7159%. The 5.5159% discrepancy indicates a difference in characteristics between the system's actual state and the simulation model. The PQ One measurements reflect actual conditions involving a mix of various industrial loads, while the Simulink model focuses on a specific nonlinear load scenario—namely, a six-pulse diode rectifier. Consequently, the simulation results serve as an approach to identifying the harmonic characteristics of nonlinear loads rather than as a direct validation of the field measurements.

Table 7. Comparison of PQ ONE and Simulink Results Harmonic Measurement Results Using PQ One

Parameter	Result
THD-I rata-rata	7,20%
Compliance H5	73,87%
Compliance H7	88,20%

Harmonics Simulation Results Using Simulink	
Parameter	Result
H1	441,4513 A RMS
H5	51,6665 A RMS
H7	19,5684 A RMS

Based on Table 6, the THD-I measured by the PQ One device shows an average value of 7.20%, whereas the Simulink simulation yields a THD-I of 12.7159%. The 5.5159% discrepancy indicates a difference in characteristics between the system's actual conditions and the simulation model. The PQ One measurements reflect actual conditions involving a combination of various industrial load types, while the Simulink model focuses on a nonlinear load scenario featuring a six-pulse diode rectifier. The 5th and 7th-order harmonics observed in the simulation results exhibit the characteristic behavior of a six-pulse rectifier. These results demonstrate that an increase in nonlinear loads can lead to higher levels of current distortion compared to the system's average actual operating conditions. Consequently, Simulink can serve as a supporting tool for analyzing

transformer response under conditions of higher harmonic levels.

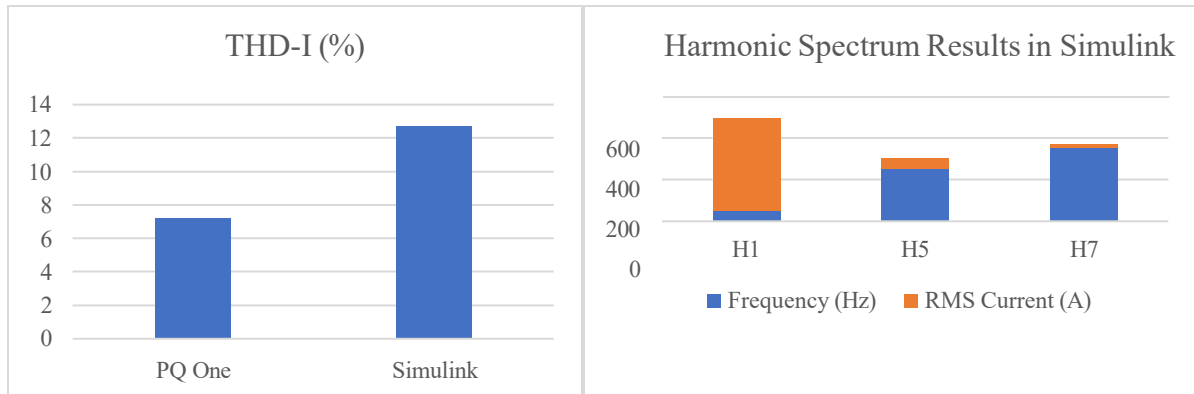


Figure 8. Comparison of RMS Current from PQ ONE Measurement Results and MATLAB Calculations

Analysis Of The Effect Of Simulink Results On RMS Current

Simulation results were used to analyze the relationship between the increase in THD-I and changes in RMS current for a 1600 kVA transformer. Based on the characteristics of non-sinusoidal current, the RMS current can be expressed as the resultant of the fundamental and harmonic components; consequently, an increase in THD-I leads to a rise in the effective current value. At a THD-I level of 7.20%, the RMS increase factor is mathematically approximately 1.00259, representing an effective current increase of about 0.259%. In scenarios with THD-I levels of 10%, 15%, and 20%, the increases in RMS current reached approximately 0.50%, 1.12%, and 1.98%, respectively. These results demonstrate that increased harmonic distortion contributes to a rise in RMS current, a factor that must be considered when evaluating transformer loading.

Table 8. Effect of THD-I on RMS Current

THD-I Increase	in RMS Current	Increase Loss Indicator I ² R
0%	0%	0%
5%	0,125%	0,25%
7,20%	0,259%	0,52%
10%	0,50%	1,00%
15%	1,12%	2,25%
20%	1,98%	4,00%

Based on Table 7, the change in losses in this analysis is expressed as a relative index derived from the relationship $P \propto I^2R$. This value illustrates the trend of loss variations resulting from increases in RMS current, rather than representing an actual measurement of transformer power losses in watts. At a THD-I of 7.20%, the RMS current increased by 0.259%, with a corresponding loss increase indicator of 0.52%. When THD-I rose to 20%, the RMS current increased by 1.98%, while the loss increase indicator rose by 4.00%. These results demonstrate that harmonic components raise the effective current value, thereby leading to a relative increase in conductive losses. The values in the table serve as mathematical indicators based on the I^2R relationship and do not represent direct measurements of temperature rise or actual transformer losses. Consequently, the simulation results serve as a preliminary indicator of the relationship between THD-I and the increase in effective current, rather than as absolute values for transformer losses.

5th And 7th Order Harmonic Analysis

An analysis of the 5th and 7th order harmonics was conducted because these components are key characteristics typically found in systems utilizing six-pulse rectifiers. PQ ONE results indicate that the 5th and 7th orders were among the evaluated current harmonic parameters, with a limit of 4.0% for each in the measurement report. The average compliance rates derived from the data were 73.87% for the 5th order and 88.20% for the 7th order; however, these figures represent compliance percentages rather than harmonic magnitudes. In the Simulink simulation, the 5th and 7th order components registered values of 51.67 and 19.57, respectively, on the Spectrum Analyzer. Thus, the presence of the 5th and 7th orders in both analyses demonstrates that these harmonic components require attention when evaluating nonlinear loads on transformers.

Table 9. Harmonic spectra from Simulink simulation for components H1, H5, and H7.

Harmonic Order	Frequency (Hz)	RMS (Vrms)	Relative Power (dB)
H1	50.354	441.4513	0
H2	99.1821	0	-441.451
H3	151.062	0.0005	-441.451
H4	201.416	0.0007	-441.451
H5	250.2441	51.6665	-389.785
H6	302.124	0.0004	-441.451
H7	349.4263	19.5684	-421.883
H8	398.2544	0	-441.451
H9	450.1343	0.0004	-441.451
H10	502.0142	0.0005	-441.451
H11	549.3164	7.583	-433.868
H12	601.1963	0.0005	-441.451
H13	650.0244	6.4202	-435.031
H14	700.3784	0	-441.451
H15	750.7324	0.0004	-441.451
THD	—	12.72%	—

The results from the Spectrum Analyzer illustrate that the fundamental component (H1) lies at 50.3540 Hz with an RMS value of 441.4513 A, while the 5th (H5) and 7th (H7) harmonics occur at 250.2441 Hz and 349.4263 Hz and RMS values of 51.6665 A and 19.5684 A, respectively. The THD-I value acquired from the simulation equals 12.7159%, which implies that the H5 component is more dominating than H7. According to the characteristic harmonic order of the six-pulse rectifier, $h = 6k \pm 1$ the 5th and 7th harmonics are supposed to be dominant components. The PQ One results also illustrate lower compliance for H5 (73.87%) than H7 (88.20%), which makes H5 relatively more critical in the measured system. Nevertheless, the compliance values illustrate the degree of conformity to the harmonic limits and do not represent the absolute harmonic current magnitude; thus, harmonic magnitude and compliance should be considered independently.

Analysis of the Effect of Harmonics on Transformer Loading

Based on measurement results, the transformer's average apparent power was 307.1 kVA—approximately 19.19% of its 1,600 kVA nominal capacity—while the maximum apparent power reached 1,393.9 kVA, or about 87.12%. These figures indicate significant fluctuations in loading levels during the measurement period. Under high-load conditions, the increase in RMS current caused by harmonic components can raise losses that are proportional to the square of the current. However, this effect cannot be directly used to determine a derating of the transformer's nominal capacity without an analysis of thermal factors and actual losses.

Table 10. Effect of THD-I on Transformer Loading Indicators

THD-I (%)	RMS Current Factor	RMS Current Change (%)	Effective Capacity Indicator Based on RMS Factor (kVA)
0	1.0000	0.00	1600.00
5	1.0012	0.12	1598.00
7.20	1.0026	0.26	1595.87
10	1.0050	0.50	1592.06
15	1.0112	1.12	1582.30
20	1.0198	1.98	1568.92

The effective capacity indicator values based on the RMS factor in the table are the result of a mathematical approximation intended to illustrate changes in load-carrying capability due to increases in RMS current. These values do not represent an actual reduction in the transformer's nominal capacity and cannot serve as a basis for

derating without an analysis of thermal performance and measured transformer losses.

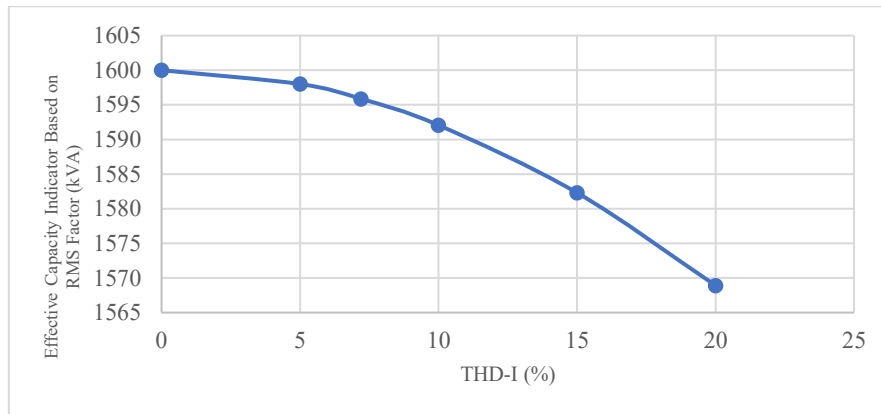


Figure 9. Effect of THD-I on Transformer Equivalent Capacity

Based on Table 8, an increase in THD-I leads to a rise in the RMS current factor and a change in the RMS-factor-based capacity indicator. At a THD-I of 7.20%, the RMS current factor rises to 1.0026—reflecting a 0.26% increase in RMS current resulting in a capacity indicator of 1595.87 kVA. At a THD-I of 20%, the RMS current factor increases to 1.0198, and the capacity indicator becomes 1568.92 kVA. These values are the result of mathematical calculations based on the RMS current increase caused by harmonic components; they do not represent a reduction in nominal capacity or the actual thermal derating of the transformer. Determining the actual derating requires a more comprehensive analysis of losses, temperature, and the transformer's thermal characteristics.

TECHNICAL IMPLICATIONS OF THE ANALYSIS RESULTS

Measurement results indicate an average THD-I of 7.20% for the actual system, whereas the six-pulse rectifier simulation yielded a THD-I of 12.7159%. This discrepancy suggests that the nonlinear load scenario in the Simulink model produces higher distortion than the average conditions observed in the actual system. Theoretically, an increase in THD-I raises the RMS current, potentially increasing losses proportional to the square of the current—particularly during periods of high loading. This warrants attention, as measurements show the transformer reaching load levels of up to 87.12% of its nominal capacity. Consequently, periodic monitoring of THD-I and RMS current is essential, especially given the increasing use of power electronics-based loads.

Some mitigation methods involve identifying the main causes of harmonics, performing periodic THD-I measurements, and applying harmonic filters in case of increased levels of distortion[32][33]. It is essential to perform phase balancing of loads, since measurements have shown that different values of THD-I and RMS current have been detected for different phases. Depending on the nature of the harmonic spectrum, various solutions can be applied. The mitigation techniques must be employed according to the measured values at the point of evaluation to allow the accurate choice of the filter capacity and type[32][34]. By doing this, one will manage to control the harmonic distortion and maintain the transformer's performance.

CONCLUSION

Based on measurement results using the Hioki PQ3198 via PQ One, the 1600 kVA distribution transformer in actual operating conditions has an average THD-I value of 7.20%, with values for the R, S and T phases respectively of 6.53%, 7.58% and 7.50%. The measurement results also show that the average apparent power is 307.1 kVA or around 19.19% of the transformer's nominal capacity, while the maximum load reaches 87.12%. MATLAB calculations using fundamental current parameters and THD-I measurement results produce RMS currents of 462,282 A, 439,658 A, and 454,373 A in the R, S, and T phases, with an average difference of 0.154% to the RMS value recorded on the PQ One. THD-I variations prove that any rise in distortion leads to a quadratic increase in RMS current and relative losses; hence, it is crucial to take note of this aspect, particularly at high loads. Simulink simulation using a six-pulse diode rectifier produces a THD-I of 12.7159% with 5th and 7th order harmonic components of 51.6665 A RMS and 19.5684 A RMS respectively. These results show different harmonic characteristics of actual operating conditions because the Simulink model represents certain nonlinear load scenarios, while the PQ One data represents industrial systems with a combination of various load types. Thus, MATLAB/Simulink can be used as an analytical approach to evaluate the influence of THD-I variations and nonlinear load characteristics, while Power Quality measurements provide a representation of the actual operating conditions of the transformer.

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