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Harmonics Assessment of Distribution Transformer with Photovoltaic Integration and Unbalanced Loads

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Abstract: Harmonic distortion is one of the monumental power quality problems in an electrical power system. It frequently originated from non-linear loads generating non-sinusoidal steady state waveforms, which may lead to various undesirable effects on distribution transformers such as increased losses, overheating and lifetime reduction. In previous works, the harmonic current contributions from non-linear loads from consumers have been appointed as the main contributor of harmonic issues in the distribution transformers. However, since the integrations of renewable energy as a distributed generation (DG) have exponentially increasing in recent years, the impact of solar photovoltaic (PV) system implementation into distribution system on amplifying additional harmonic contents also needs to be addressed. Therefore, this paper conducts a comparative analysis of voltage and current harmonic profiles within the distribution transformer in three-phase distribution network and three-phase grid-connected photovoltaic (GCPV) system, with both subjected to supply unbalanced non-linear loads. The simulation is carried out using MATLAB Simulink 2021a software and the results are compared according to standards. As a result, the distribution transformer in the GCPV system is proven to contain higher levels of voltage and current harmonic distortion compared to a normal distribution grid.

Keywords: Distribution Transformer, Harmonic Distortion, Photovoltaic System

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1. INTRODUCTION

Power systems support the reliable distribution of power to households, businesses, and industries, acting as the backbone of contemporary life. However, even in these complex systems, harmonic distortion is one of the power quality problems that cannot be avoided. Harmonic distortion refers to the deviation of alternating current (AC) from the ideal sinusoidal waveform. It happens when non-linear loads such as electronic gadgets and power electronics devices are added to the system. Harmonics are additional frequencies that are integer multiples of the fundamental frequency. For instance, the presence of harmonics may add frequencies like 100 Hz, 150 Hz, and so forth into a system having a fundamental frequency of 50 Hz [1]. These harmonics may have a number of negative repercussions on the power system. In an electrical distribution system, transformers are crucial components that facilitate efficient transfer of electrical energy between different voltage levels. Therefore, the presence of harmonics may introduce adverse effects to the transformer such as increased in losses, overheating, compromise the insulation system, accelerate aging, and potentially result in insulation failure or even catastrophic damage [2], [3]. On the other hand, with the exponentially increasing renewable energy integration in distribution system, solar PV systems, in particular, have also impacted the power quality problem [4], [5], [6]. The harmonics introduced by the PV systems and its inverters can interact with the existing harmonics generated by other non-linear loads in the distribution system, further complicating the harmonic profile of the transformers. This interaction may lead to amplification of specific harmonic frequencies, resulting in a different harmonic spectrum in the transformer. Therefore, harmonics analysis in the distribution transformer for both systems is crucial for ensuring the sustainable and reliable operation within power systems.

According to the existing literature, most of the previous works addressed non-linear elements from consumers side as the sole contributor to the current and voltage harmonic distortion within the transformer. In [7], the authors highlighted the current harmonics level increment due to rectifiers and PWM drives. Different numbers of amplitudes are found in the current waveform passing through the transformer windings. The authors in [8] emphasized harmonic current from non-linear load contributes on eddy current loss rise. The related impacts of non-linear loads on both voltage and current THD have been analyzed in [9], [10] and being compared to IEEE standard. However, limited research has focused on the comprehensive comparison of the impact of PV-induced grid system on the harmonic content of transformers. Although several works have explored the influence of PV systems on the transformer performance, it appears that the concurrent effect of non-linear loads on both voltage and current distortion in the transformer has often been neglected [11], [12], [13], [14]. Therefore, as a novelty of study, this paper conducts a comparative analysis on current and voltage harmonic distortion of a 200 kVA distribution transformer in the presence of unbalanced non-linear loads, with and without PV system integration. The simulation is executed using MATLAB Simulink 2021a software. By incorporating the influence of nonlinear loads and PV induction on the harmonic profiles, a more holistic understanding on the impact can be achieved.

2. METHODOLOGY

This section explains the methodology of this study, which consists of equipment specifications, such as distribution system, substation transformer specification, and PV system. The detail for the simulation model using MATLAB Simulink is also clarified in this section.

2.1 Distribution Transformer Specifications

The distribution transformer is modeled to exhibit the characteristics of the real distribution transformer in a low-voltage network. The two-winding transformer with delta-star winding configuration is modeled in MATLAB Simulink. The specifications for distribution transformer are as in Table 1.

Table 1. Distribution Transformer Specifications

Specification	Value
Capacity	200 kVA
Primary Voltage	11,000 V
Secondary Voltage	400 V
Frequency	50 Hz
Short Circuit Capacity, MVA_{sc}	7 MVA
Maximum Short Circuit Current, I_{sc}	10115 A
Maximum Demand Load Current, I_L	289 A
Short Circuit Current Ratio, I_{sc}/I_L	35 A

2.2 Photovoltaic System Description

In order to analyze the difference in harmonics content in the transformer, the photovoltaic system is connected with the distribution grid. Therefore, the specifications of the PV system implemented are as in Table 2.

Table 2. Photovoltaic System

Specification	Value
Power Output per Panel (W)	213.15
Number in Series	10
Number in Parallel	10
Irradience (W/m^2)	1000

2.3 Distribution System Model

In this study, there are two systems used in order to analyze and compare the harmonic content in the distribution transformer. Therefore, two sets of models are designed which are a normal three-phase distribution grid and a three-phase grid-connected photovoltaic system (GCPV). The details of the simulation model are explained as follows.

2.3.1 Normal Distribution Grid Model

The first model was designed in MATLAB Simulink to demonstrate a normal distribution grid as depicted in Figure 1. A 200 kVA step-down transformer is placed between a 100 MVA three-phase grid source with a base voltage of 11kV, which to be stepped down to 400 V to serve the three-phase unbalanced non-linear loads as the consumers.

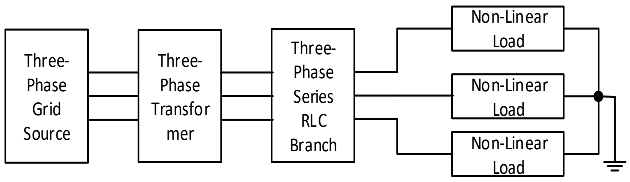

Figure 1. Normal Distribution Grid Model

2.3.2 GCPV System Model

The second model was developed with the objective of demonstrating a GCPV system, which achieved through the integration of PV system into the distribution grid. Therefore, Figure 2 illustrates the schematic diagram of a three-phase grid-connected PV system. The system contains PV arrays, with the specifications portrayed in Table 2, an inverter is placed to convert the produced energy from DC to AC power source and also a DC-DC boost converter. The PV system is connected to the utility grid at the point of common coupling (PCC) through the output of the LCL filter.

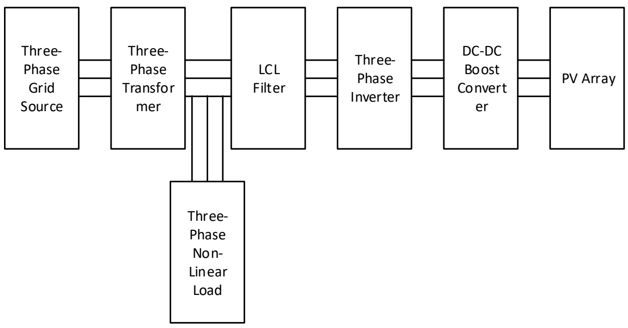

Figure 2. Grid-Connected Photovoltaic System Model

2.3.3 Unbalanced Non-linear loads Configuration

Meanwhile, in order to emulate the unbalanced non-linear loads at the consumer side for both systems, the type of load modeled in this study is a rectifier supplying unbalanced loads consisting of resistor and inductor, where the values are indicated in Table 3. A rectifier was chosen in this case as it injects excessive distortion on the voltage and current waveform compared to thyristor and MOSFET. Therefore, the configuration of the unbalanced non-linear loads for each phase was modeled as depicted in Figure 3.

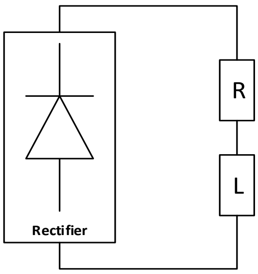

Figure 3. Non-Linear Load Consisting Rectifier Supplying Unbalanced Load

Table 3. Load Impedance Values

Load Phase	Resistance (Ω)	Inductance (mH)
Phase A	1.5	22
Phase B	1.25	17
Phase C	1	11

2.4 Formulations and Standard Limits

Since this study is focusing on the harmonics for low-voltage distribution network, the standards of MS 1555:2002 (IEC TS 61000-3-4:1998) [15] and IEEE Std 519-2014 [16] are chosen as a reference to monitor the permissible limits for the current and voltage distortion in the network, respectively.

2.4.1 Harmonics Distortion Formulations

Institute Electrical and Electronic Engineers (IEEE) quantified harmonics based on the root mean square values of the fundamentals. Equation (1) and (2) are the formulations for individual harmonic distortion, indicating the contribution of each harmonic frequency to the total harmonic distortion of a waveform in the form of percentage. It is calculated by dividing the RMS value of each harmonic by the RMS value of the fundamental frequency [16].

$$IHDi_n = \frac{I_n}{I_1} \tag{1}$$

$$IHDv_n = \frac{V_n}{V_1} \tag{2}$$

Total harmonic distortion (THD) can be defined as the net deviation of non-linear waveform generated compared to ideal sinusoidal waveform characteristic. The THD can be calculated as the ratio between the RMS value of the individual harmonics and the RMS value of the fundamental waveform. Equation (3) and (4) presents the THD calculation which also presented in percentage form [16].

$$THDv = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{3}$$

$$THDi = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{4}$$

2.4.2 Harmonic Distortion Standard Limits

There are several International standard bodies that provide the standard and guidelines for harmonic distortion limits for various levels of distribution networks. Therefore, the standard limit of MS 1555:2002 (IEC TS 61000-3-4:1998) is used for current distortion reference while IEEE Std 519-2014 is the standard chosen to be referred for voltage distortion in the low-voltage distribution network. Table 4 and Table 5 depict the voltage and current distortion limits, respectively.

Table 4. Harmonic Current Distortion Limit [15]

Harmonic number, n	Admissible harmonic current, $\frac{I_n}{I_1}$ (%)	Harmonic number, n	Admissible harmonic current, $\frac{I_n}{I_1}$ (%)
3	21.6	21	≤ 0.6
5	10.7	23	0.9
7	7.2	25	0.8
9	3.8	27	≤ 0.6
11	3.1	29	0.7
13	2.0	31	0.7
15	0.7	≥ 33	≤ 0.6
17	1.2		
19	1.1	Even	≤ 8 I_n or ≤ 0.6

Where I_1 is the rated fundamental current and I_n is the harmonic current component. It is important to note that this analysis considers odd harmonic components up to 19th harmonic order.

Table 5. Voltage Distortion Limits [16]

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion (%)
$V \leq 1.0$ kV	5.0	8.0
1kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Meanwhile, since the bus voltage value at the PCC of the test system is 400 V, the THDV limit of 8.0% is chosen as the voltage distortion limit.

3. RESULTS AND DISCUSSIONS

To analyze the harmonic content on the distribution due to the inclusion of PV systems in the grid network, the analysis is observed for both current and voltage harmonics which will be explained in Section 3.1 and 3.2.

3.1 Total Harmonic Distortion Current (THDI) Comparison

Table 6 shows the THDI measurement of the distribution transformer from the simulation. For the normal grid condition, the value of THDI for phase A, phase B and Phase C are 6.14%, 5.15%, and 3.87% respectively. However, the PV-Grid condition on the other hand shows the opposite outcome, where there are differences in the amount of distorted current produced within the distribution transformer as the value of the THDI measured is slightly higher compared to the normal grid condition with the value of 10.81%, 10.44% and 10.81% for Phase A, Phase B and Phase C respectively. Figure 4 illustrates the comparison chart for the THDI of the transformer for each phase cable between the normal grid and GCPV grid system.

Table 6. Phase THDI

Grid Mode	THDI Phase A (%)	THDI Phase B (%)	THDI Phase C (%)	Average THDI (%)
Normal	6.14	5.15	3.87	5.05
GCPV	10.81	10.44	10.81	10.69

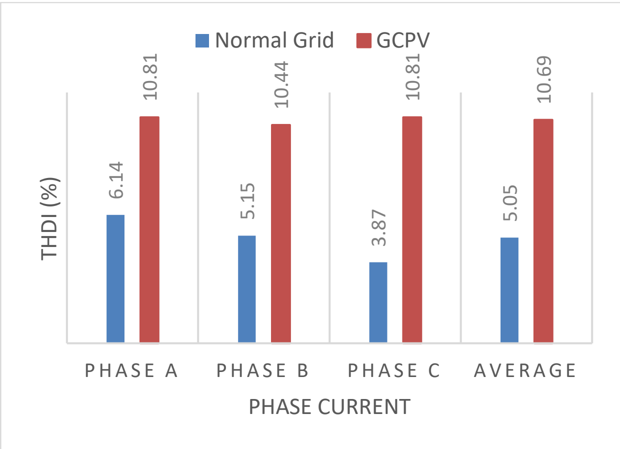

Figure 4. Phase THDI Chart

Table 7 and Figure 5 depict the Individual Harmonic Distortion for the normal grid and GCPV grid. From the simulated curve, the results indicated that the PV-Grid mode consistently produced higher harmonic percentage at each harmonic order compared to the normal distribution grid condition. This is due to the additional presence of the non-linear element in the system which is an inverter in the GCPV system which converts the variable DC voltage from the PV array into AC voltage and frequency to the grid. The non-linear behavior of power electronic components in the inverter including IGBTs and diodes did not generate a clean sinusoidal waveform during the conversion process due to the switching nature of the aforementioned devices. As a result, the Individual Harmonic Distortion (IHD) current at each odd harmonics, from 3rd harmonic to 19th indicate a massive difference between both grid modes. Based on the referred standard limit of MS 1555:2002 (IEC TS 61000-3-4:1998), it can be observed that the harmonic currents for the normal grid remain under the admissible harmonic current level. While for the GCPV transformer, the harmonic current at 15th order has violated and surpassed the limit by 0.21%.

Figure 6 illustrates the RMS current generated at the secondary winding of the transformer for each odd harmonic order. From the comparison, it can be seen that the RMS current appears to be higher in the GCPV case as compared to the normal grid case. The differences solidify the fact that the presence of PV systems has influenced the harmonic current content and contributes to the increment of the total harmonic distortion values.

Table 7. Transformer Harmonic Current, I_h

Harmonic Order	Harmonic Current in Normal Grid (%)	Harmonic Current in GCPV (%)	Admissible Harmonic Current [MS 1555:2002 IEC TS 61000-3-4:1998] (%)
3	4.86	10.22	21.60
5	1.09	2.02	10.70
7	0.67	1.2	7.20
9	0.38	1.1	3.80
11	0.25	0.37	3.10
13	0.19	0.76	2.00
15	0.13	0.91	0.70
17	0.11	0.68	1.20
19	0.08	0.2	1.10

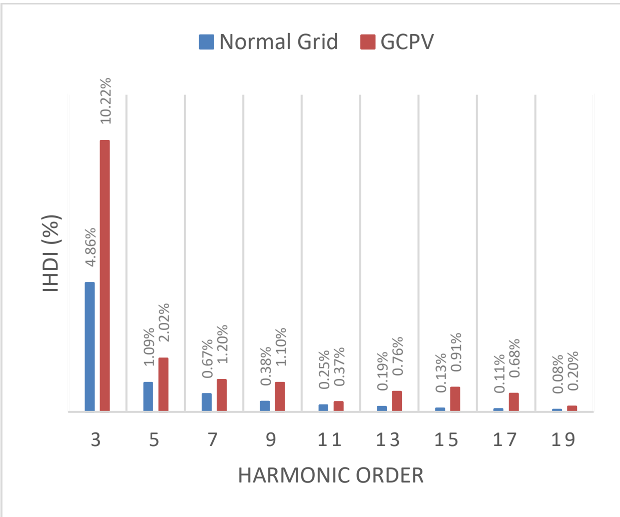

Figure 5. IHD Current Comparison

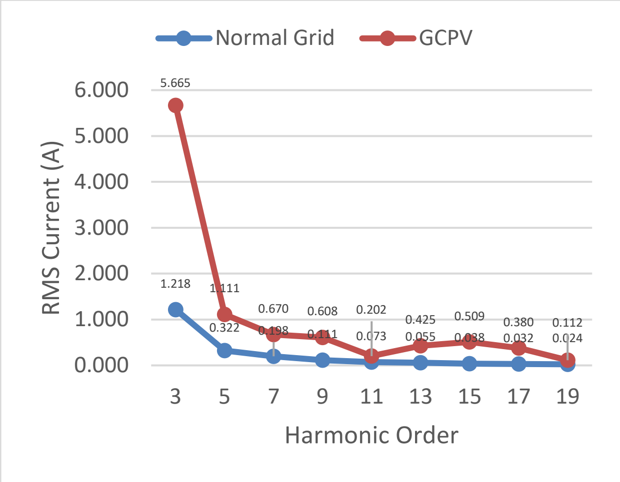

Figure 6. Odd Harmonic RMS Current

3.2 Total Harmonic Distortion Voltage (THDV) Comparison

Table 8 and Figure 7 present the total harmonic distortion voltage (THDV) of the transformer at each phase for both grid modes. The results indicate that different load values at each phase produce different levels of voltage harmonics. In both grid systems, Phase A has the higher impedance value while phase C has the lightest load value. As a result, Phase A has the highest THDV values compared to Phase B and Phase C. The significant difference in THDV values is proven as the average THDV of a normal grid mode increased from 2.24% to 7.26% of GCPV mode. Therefore, it can be concluded that the higher the impedance value, the higher the THDV produced at the corresponding phase.

Table 8. Phase THDV

Grid Mode	THDV Phase A (%)	THDV Phase B (%)	THDV Phase C (%)	Average THDV (%)
Normal	2.71	2.29	1.73	2.24
GCPV	7.11	7.16	7.51	7.26

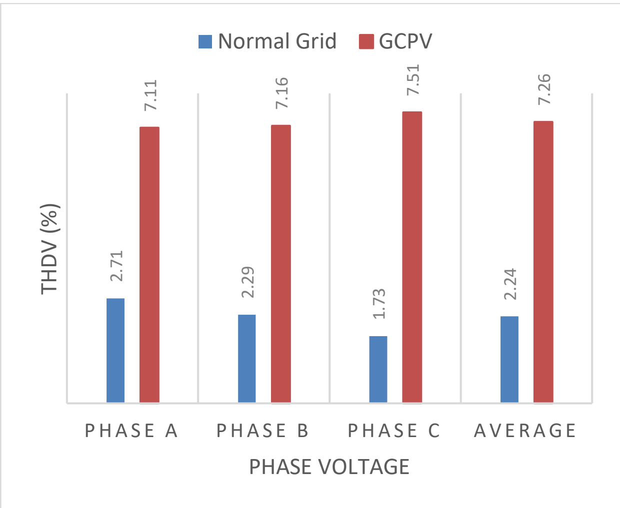

Figure 7. Phase THDV Chart

Table 9 and Figure 8 illustrate the comparison between IHD values for both grid modes. For the normal grid condition, even though there are higher harmonic distortion values indicated on the low harmonic orders compared to PV-grid mode, the implementation of the PV system and its associated inverter have influenced the higher order parts starting from 9th until 19th, consequently producing higher THD. It proves that without a PV system, the only source of harmonics on the power grid is coming from the nonlinear loads at the consumer sides, such as rectifiers, computers, fluorescent lights, and electric motors. These loads characteristically only generate odd harmonics. Meanwhile, Figure 9 portrayed the comparison of the RMS voltage for odd harmonic orders. In the same case as the IHD values, the presence of PV system started to influence the RMS current from 9th harmonic orders onwards.

Table 9. IHD Voltage Comparison

Harmonic Order	IHD of Normal Grid (%)	IHD of GCPV (%)
3	1.60	0.92
5	0.86	0.49
7	0.57	0.49
9	0.58	0.88
11	0.36	0.61
13	0.39	1.00
15	0.30	1.64
17	0.27	1.38
19	0.26	0.55

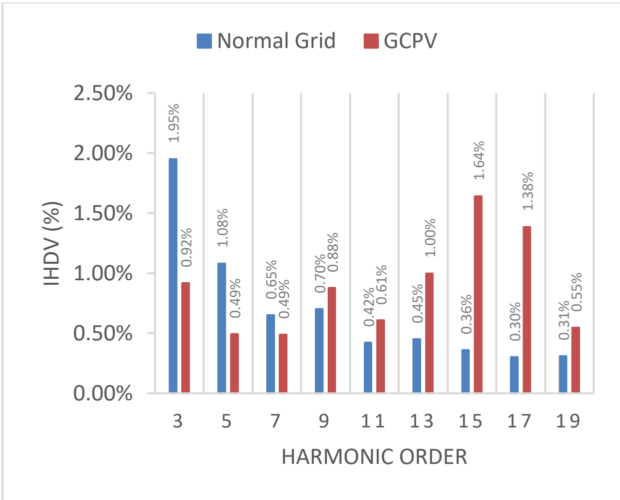

Figure 8. IHD Voltage Comparison

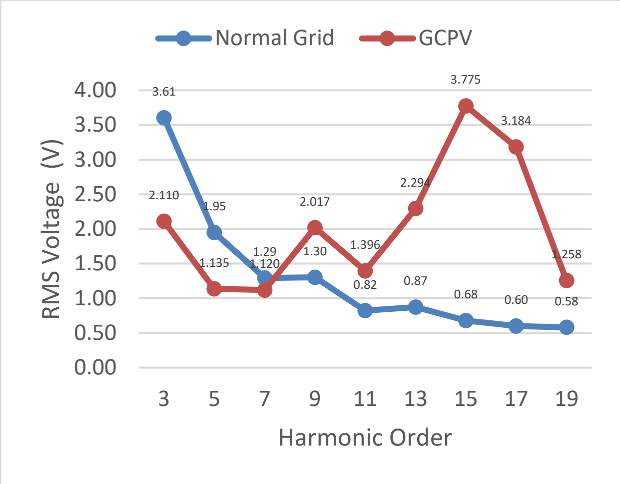

Figure 9. Odd Harmonic RMS Voltage

4. CONCLUSION

The evaluation of current and voltage harmonics of a distribution transformer has been done between a normal distribution grid and a grid-connected photovoltaic system. From the study, it proved that the higher the value of phase load impedance, the higher the THD produced in the corresponding phases. Besides, the simulation results showed significant differences in the distorted current and voltage values, where the transformer in GCPV system having higher THD value due to the accumulated nonlinear generation of current and voltage waveform from the three-phase unbalanced load with the addition of power electronic inverter from the PV system implementation. Regarding the standard limit comparison, the current distortion values of the transformer in the normal grid remain under the limits while for the transformer current in the GCPV system, each component maintains under the limit except for the15th harmonic order where it surpassed the limit by 0.21%. On the other hand, for voltage harmonic distortion, even though the THDV level of the transformer in the GCPV system is proven higher than the normal grid condition, both conditions depict values under the limit of 8%. Even though the simulation results did not indicate any significant limit violation, it is important to note that when the loading changes, there is a high possibility for the harmonic current and voltage to exceed the recommended value. Lastly, it is important to conclude that PV-grid integration can increase the harmonic distortion appearance in a distribution transformer, which consequently can cause inimical effects in terms of performance and lifespan of the distribution transformer.

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