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(Research Article)

Harmonic distortion-based condition monitoring of distribution transformers in a solar farm

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Abstract

This paper presents a condition monitoring approach for distribution transformers in solar farms, focusing on analysing harmonic distortion. The methodology leverages the IEEE standard to evaluate the severity of harmonic pollution in the transformer's operating environment. Specifically, the research investigates Total Harmonic Distortion (THD), Total Demand Distortion (TDD), and Individual Harmonic Distortion (IHD) through real-time data measurements. These parameters are essentially the majority in distinguishing transformer degradation from increased losses, over-heating and insulation stress brought about by non-linear loads inrush currents. In this study, the operating characteristics of the six station transformers supplying converters as non-linear loads are examined and the influence of THD on voltage current power loss and transformer efficiency is rated. A case study is conducted on a 1400 kVA three-phase transformer feeding a rectifier connected to a symmetrical inductive load. The analysis compares the PCC and the measured harmonic levels based on the IEEE standard to identify thermal faults and evaluate the operating condition of the transformer. Transformers 3 and 6 are characterized as overheated due to elevated temperature in combination with high load percentages (86% and 84% respectively) and moderately high THDI values (10% to 12%). Transformers 1, 4 and 5 are labelled with a high THDI value because their current harmonic distortion values (between 11% and 14%) clearly exceed the recommended limits. By monitoring these harmonic indices, this approach provides a proactive method to detect and mitigate harmonic-related problems, extend transformer life and improve power system reliability. The results emphasize the importance of adhering to standard guidelines for maintaining optimal transformer performance and ensuring power quality in distribution networks.

Keywords: Distribution transformers; Photovoltaic (PV); Total Harmonic Distortion (THD); Condition monitoring

1. Introduction

The increased demand for renewable energy around the globe has hastened the development and usage of solar photovoltaic (PV) systems [1]. Distribution transformer in solar energy farms is a critical component of the entire solar energy distribution grid, both for voltage regulation; grid-connection of solar farms. The effective operation of these transformers is essential to prevent unplanned outages, energy losses and equipment damages [2] [3], thus their reliability and operating efficiency must be maintained. Sufficient and dependable performance of these devices is essential for the continuity of power supply as well as power quality. Nevertheless, the rise of more non-linear loads such as variable frequency drives, electronic ballasts and power electronic devices poses one major problem regarding

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the robust state and life expectancy of these transformers [2], [4]. Non-linear loads produce harmonic currents and voltages from the ideal sinusoidal waveform that is causing harmonic distortions in the power system [5]. Such distortions may badly affect distribution transformers as for example higher losses, overheating, insulation degradation and service life reduction [6]. Thus, the need for reliable condition monitoring techniques in order to determine if these transformers are operating as expected and mitigate some repercussions of harmonic distortion are essential.

As we know that presence of harmonics in solar power system is not a good, the distribution transformer has many impacts due to this for harmonics. Skin effect increases the skin fraction of cross-sectional area, further proximity effect increases copper losses at higher frequencies [7]. Due to these extra losses the operating temperatures are up and may exceed thermal limits in transformer, quick decay of insulation [8] Higher operating temperatures result, due to additional losses that may exceed the thermal limits for the transformer and insulation deteriorates fast [9]. Moreover, the harmonic voltages of hysteresis and eddy currents will make the core losses bigger and this adds to thermal stress on the transformer [9] Transformer: dielectric stresses in insulation system are due to distortion of voltage & current waveforms [10]. The peak harmonic voltages could be more than the insulation rated value which might cause partial discharges and failure of insulation [11]. It stimulates resonant phenomena inside the power system, which generates or amplifies harmonic levels and manifests itself as voltage/current distortions on the whole system. This can lead to malfunctioning of devices, failure of protection systems and even grid instability. Vicente León-Martínez et al. [4] presents the load losses that occurred during the evaluation of distribution transformers under no-load conditions in view of the harmonic currents in their study. The authors improve on the conventional methods of calculating losses based on ANSI and IEEE standards by considering the asymmetric harmonic loading across the phases of the transformer. Imtiaz Ahmed et al. [2] lists all possible harmonics influences associated with power systems from different sources. The authors classify nonlinear devices including power electronic converters, variable frequency drives (VFDs), and uninterruptible power supplies (UPS) and arc furnaces as a key contributor to harmonic pollution of modern power grids. Morteza Mikhak-Beyranvand et al. [6] analysis of power transformers under harmonic load. They improve the thermal equivalent circuit (TEC) for oil-filled transformers by evaluating the temperature distributions of all components of the transformer, including the windings, core, tank and clamping materials, and developing the additional losses caused by harmonic currents using a three-dimensional finite element method and thermal stresses. Eduardo Tavares Silvério et al. [7] researches the measurement and modelling of the skin effect in conductors during the analysis of harmonic current flow. They find that harmonic frequencies significantly increase the resistance of the conductor, with the resistance increasing by up to 1.9%. To improve the modelling and reduce the simulation time, they propose frequency-dependent mathematical models of the skin effect developed in Open DSS. They show that the simulation time could be reduced by 17 and point out that omitting the skin effect can lead to an underestimation of technical losses in distribution systems. Milad Dalali et al. [12] are working on improve the methods for measuring harmonic distortion. They are analysing traditional indices such as THD, THDS and THDG and their limitations in capturing inter harmonic distortion. To improve the measurement accuracy, the authors develop new indices, THDGS and ITHDG, which are based on virtual groupings of harmonics.

Distribution transformer condition monitoring to combat the emerging challenges Condition Monitoring of distribution transformers is becoming more and more important. The traditional monitoring methods pay attention to temperature, oil condition and insulation resistance [11]. These methods are helpful in knowing the transformer in overall better but may not be enough to reflect their bias in harmonic distortion. Thus, it is important to add harmonic analysis along in Condition monitoring [13]. Measuring and analysing specific harmonic parameters like Total Harmonic Distortion (THD), Total Demand Distortion (TDD) & Individual Harmonic Distortion (IHD) [12, 14] The severity of harmonic distortion and its concern for transformer is will view through Pinching this transformer [12], [14] These appraisals the effects of harmonics on distribution transformers by and will help in comparing the performance parameters of transformers with the IEEE 519-2014 guidelines. Continuous or regular monitoring of these harmonic levels enables early detection of trends and potential problems that, if corrected in time, can prevent serious failures. This approach supports proactive condition monitoring and facilitates timely maintenance measures, such as the installation of harmonic filters or the redirection of non-linear loads. Harmonic analysis is used in the transformer monitoring which is integrated with operational efficiency by minimizing thermal stress and better load management. It moreover increases the lifetime not only of transformer but the complete distribution reliability and quality of electrical power supply in solar parks [15].

2. Methodology

This paper studies how monitoring approach is applied on evaluation a distribution transformer applied in a car park solar farm [16]. It uses harmonic indices for quality of power to improve the efficacy on operation of transformers by applying this method. Total Harmonic Distortion (THD), Total Demand Distortion (TDD) and Individual Harmonic Distortion (IHD) Here we analyses these three parameters primarily. Table 1: Voltage distortion expressed in THD and

IHD which specifically measure and Table 2 provides the evaluation of TDD, current distortion. IEEE Standard 519-2014, which establishes recommendations for limiting distortion harmonic to guarantee the efficacy and reliability in operation of the power system [17]. All data were measured based on Point of Common Coupling (PCC). The (PCC) is the point in an electrical power system where multiple user or load are connected to a common utility supply. It is typically the interface between a power utility and a customer's electrical system. The PCC is important in power quality analysis especially when assessing harmonic distortion, voltage fluctuation and other disturbances [18].

2.1. Total Harmonic Distortion (THD)

In the context of power quality and performance for a modern electrical network [19], one of the most important parameters is the Total Harmonic Distortion (THD) [19]. THD indicates how much of actual voltage or current waveform differs from the pure sinewave harmonic of non-linear load. THD quantifies the harmonic content in relation to the fundamental frequency and the THD express in equation 1.

$$THD = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1}} \times 100\% \qquad (1)$$

Where, I_h is RMS current of the h^{th} harmonic and I_1 is RMS current of the fundamental frequency of first harmonic. In the presence of non-linear loads, such as inverters, rectifiers, and variable frequency drives, harmonic voltages are generated and superimposed onto the fundamental voltage waveform. Elevated voltage THD can cause significant operational issues. The Total Harmonic Distortion of voltage (THDv) is calculated using the following equation (2).

$$THD = \sqrt{\frac{\sum_{h=2}^{\infty} V_h^2}{V_1}} \times 100\% \qquad (2)$$

2.2. Individual Harmonic Distortion (IHD)

Individual Harmonic Distortion (IHD) measures the distortion level of a specific harmonic order relative to the fundamental frequency component. Unlike Total Harmonic Distortion (THD), which considers the cumulative effect of all harmonics, IHD focuses on the distortion caused by each harmonic individually. The IHD for the h^{th} harmonic is defined mathematically as in equation (3).

$$IHD_h = \frac{I_h}{I_h} \times 100\% \qquad (3)$$

Where, I_h is RMS current of the h^{th} harmon and I_1 is RMS current of the fundamental frequency.

Total Demand Distortion (TDD) compares the harmonic current to the maximum demand load current instead of the fundamental current, equation (4) express the mentioned condition where, I_{rated} maximum demand load current.

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{I_{rated}} \times 100\% \qquad (4)$$

Figure 1, shows a systematic condition monitoring scheme of distribution transformer based on transformer loading and hotspot temperature. One of the key aspects of this process involves monitoring the temperature tendency at the hotspot, the region experiencing the highest thermal stress. Excessive heating can accelerate insulation degradation, ultimately reducing the transformer's lifespan. To mitigate this risk, evaluating non-sinusoidal current condition is essential with the maximum per-unit current being determined based on the highest observed hotspot temperature.

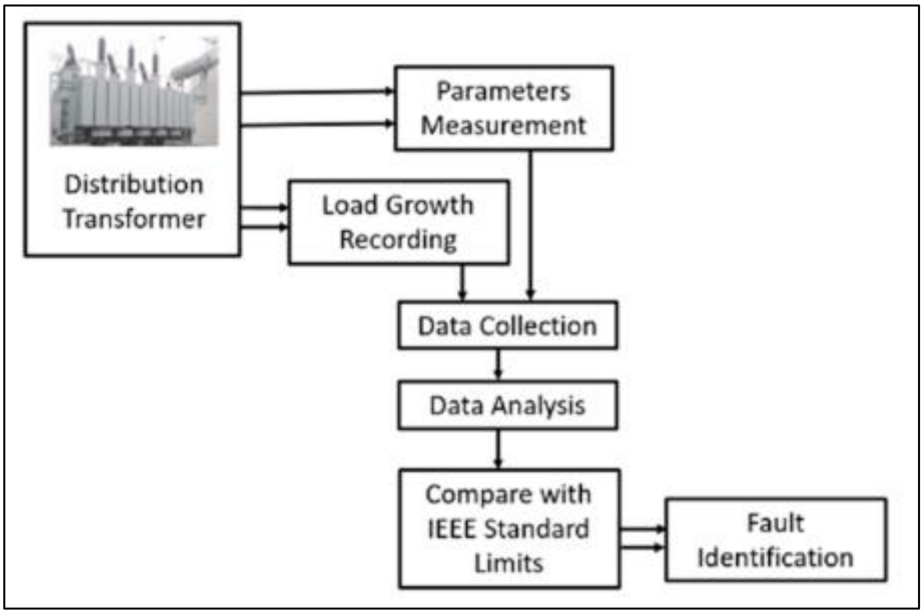

Figure 1 Distribution transformer condition monitoring scheme

The maximum per-unit current, denoted as $I_{max\text{-}pu}$, is a crucial parameter in evaluating transformer performance under varying load condition. It is mathematically defined as in equation (5).

$$I_{max}(pu) = \frac{\sqrt{P_{LL-R(PU)}}}{1+F_{HL}\times P_{EC-R}(pu)} \qquad (5)$$

Where, P_{LL-R} (pu) represents the per-unit load loss under rated operating condition, accounting for energy dissipated due to winding resistance and PEC-R (pu) denotes the per-unit eddy-current loss under rated condition. This assessment helps identify potential thermal overload that could lead to premature failure. The transformer performance evaluation is eddy-current losses (PEC-R), which are caused by stray magnetic flux inducing circulating currents within the transformer's conductive components. These losses contribute to additional heating and are calculated based on transformer specifications or historical test report data. The correction factor (FHL) further adjusts for the impact of harmonics and thermal loading effects, ensuring an accurate estimation of heating trends. By quantifying eddy-current losses, transformer efficiency can be improved, and load management strategies can be optimized.

The condition monitoring process follows a structured approach, encompassing thermal performance evaluation, current distortion analysis, and loss component assessment. A systematic asset identification process is implemented to maintain optimal transformer performance. This involves compiling a comprehensive dataset, including asset numbers, transformer series, types, and locations, while assessment records incorporate critical performance metrics such as eddy-current losses and historical transformer test reports.

Monitoring transformer condition requires continuous tracking of parameter variations over time. Load growth recording captures historical and real-time fluctuation in transformer load demand, helping to identify trends that may indicate potential overloading or operational stress. Through tendency analysis evaluating changes in load losses, eddy-current losses, and temperature variations predictive maintenance strategies are developed. Based on this analysis, transformers are prioritized according to their risk levels, ensuring that those experiencing significant stress or degradation receive timely maintenance intervention.

Table 1 IEEE standard for voltage distortion limit

Bus voltage V at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 2 Maximum harmonic current distortion in percent of IL

ISC/IL	3≤h<11	11≤h17	17≤h<23	23≤h<35	35≤h≤50	TDD
<20C	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

3. Results and Discussion

The samples of measured data are plotted in Table 3 and Table 4, represents the partial measured data filled within Table 3. The measurement shows the load current of every transformer are unbalanced based on Table 1 and Table 2. An unbalanced load causes overheating in transformers by creating uneven current distribution, leading to increased copper losses, magnetic flux imbalance, and excessive neutral or circulating current. It also introduced harmonics, which raise eddy current losses and stray flux heating, accelerating insulation degradation.

Table 3 Sample of measured actual data for six distribution transformers

Transformer	Rated KVA	Phase	Volt (V)	I_L (A)	I_p (A)	PF	THDI (%)	THDV (%)	Load KVA	Load %	Temp (°C)	Insulation
Transformer 1	1400	R	231	455	725	0.98	11	3	1150	82	48	Good
		S	230	460	735	0.97	13	4				
		T	229	470	750	0.96	14	5				
		N		180								
Transformer 2	1400	R	230	420	690	0.99	12	3	980	70	46	Good
		S	229	430	705	0.98	12	2				
		T	228	440	710	0.97	13	3				
		N		160								
Transformer 3	1400	R	232	480	755	0.97	10	2	1200	86	50	Good
		S	231	490	765	0.96	11	3				
		T	230	500	780	0.95	12	4				
		N		200								

Transformer 4	1400	R	229	430	725	0.99	12	3	1050	75	47	Good
		S	228	440	740	0.98	13	4				
		T	227	450	750	0.97	14	5				
		N		170								
Transformer 5	1400	R	231	445	735	0.98	11	3	1120	80	49	Good
		S	230	455	750	0.97	12	4				
		T	229	460	765	0.96	13	5				
		N		190								
Transformer 6	1400	R	232	470	765	0.99	10	2	1180	84	50	Good
		S	231	480	775	0.98	11	3				
		N		165								

The Table 4, presents operating parameters such as load percentage, temperature, THDI (Total Harmonic Distortion of Current), and THDV (Total Harmonic Distortion of Voltage) for six transformers. According to IEEE 519-2014, THDI values should typically be below 5% for systems with low short-circuit ratios, and THDV should not exceed 5% in any case. Transformers 1, 4, and 5 are labeled as having high THDI because their current harmonic distortion values (ranging between 11% and 14%) significantly exceed the recommended limits. This high level of distortion can lead to overheating, increased losses, and premature aging of transformer components. Although their temperatures are below critical thresholds, the sustained high THDI poses a risk to long-term reliability. Transformers 3 and 6 are marked as overheated, due to elevated temperatures (50°C) combined with high load percentages (86% and 84%, respectively) and moderately high THDI values (10% to 12%). While the voltage distortion remains within acceptable limits, the thermal stress on these transformers indicates a need for attention, possibly through load reduction or improved cooling measures.

In contrast, Transformer 2 is classified as normal. Despite THDI values reaching up to 13%, its temperature is relatively low (46°C), and THDV values are well within IEEE limits. This suggests that the transformer is operating under acceptable conditions, although the THDI values should be monitored to prevent future issues.

Table 4 Condition evaluation based on measured data

Transformer	Load %	Temp (°C)	THDI (%)	THDV (%)	Condition
Transformer 1	82	48	11, 13, 14	3, 4, 5	High THDI
Transformer 2	70	46	12, 12, 13	3, 2, 3	Normal
Transformer 3	86	50	10, 11, 12	2, 3, 4	Overheated
Transformer 4	75	47	12, 13, 14	3, 4, 5	High THDI
Transformer 5	80	49	11, 12, 13	3, 4, 5	High THDI
Transformer 6	84	50	10, 11, 12	2, 3, 4	Overheated

Figure 2, illustrates the variation between load (%) and temperature (°C) based on one time collected data for six transformers, showing a general trend where temperature increases with load. Each transformer is represented by a different color, with load percentages ranging from 70% to 86% and temperatures from 46°C to 50°C. As the load rises, the transformer temperature increases due to higher electrical losses, except for a slight dip at 82% load, which could be influenced by cooling effects or external factor.

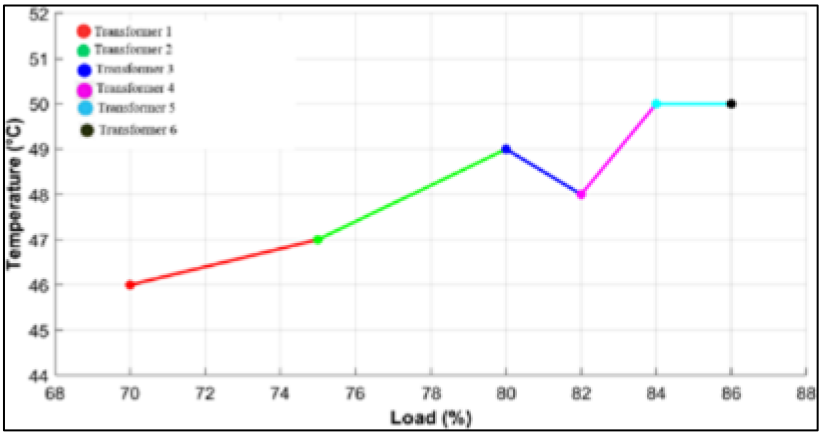

Figure 2 Variation of transformers loading

The Fig. 3, represents the variation of neutral current (A) over time, measured in hours. The neutral current fluctuates significantly, with peaks at 11:30 am (200 A) and 13:30 pm (190 A), indicating moments of high imbalance in the transformer load. The lowest recorded value occurs at 10:30 am (160 A), showing a dip in current. These variations suggest dynamic load condition, possibly due to uneven phase loading or harmonic distortion. Monitoring these fluctuation is essential for maintaining system stability and preventing excessive neutral current that can lead to overheating or power quality issues.

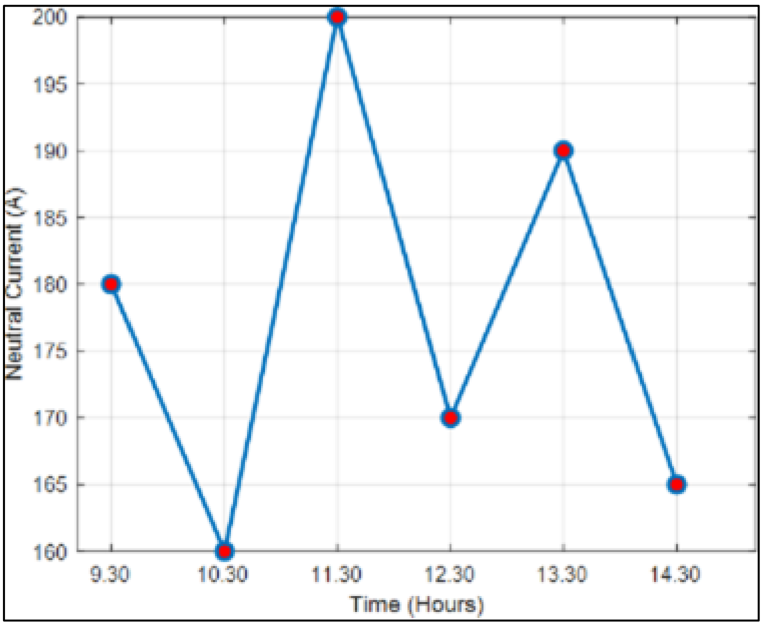

Figure 3 Variation of neutral current

The Fig. 4, shows the variation of Total Harmonic Distortion in Voltage (THD) over time. The THDV remains at 3% during 9:30 AM, 10:30 AM, 12:30 PM, and 1:30 PM, indicating stable harmonic distortion at these periods. However, a dip to 2% occurs at 11:30 AM and again at 2:30 PM, suggesting reduced harmonic interference during these times. These fluctuation in THDV may be caused by variation in load condition or non-linear load in the system.

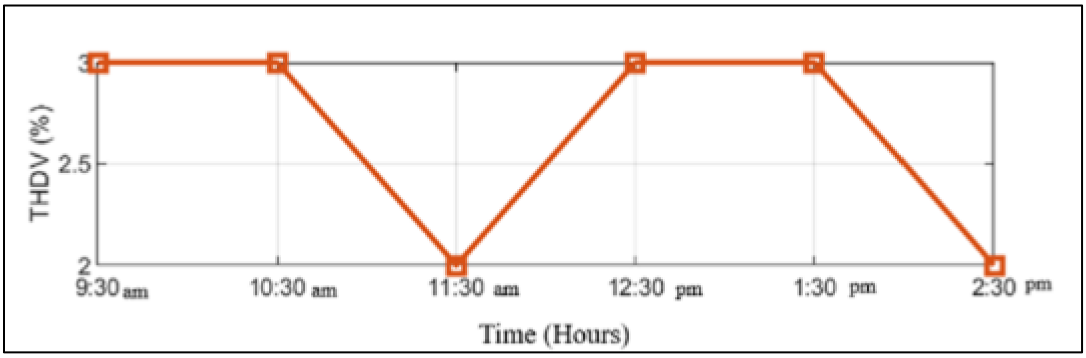

Figure 4 Total harmonic distortion in voltage over time

The Fig. 5, represents the variation of Total Harmonic Distortion in Current (THDI) over time. The THDI starts at 11% at 9:30 AM, rises to a peak of 12% at 10:30 AM, and then drops to 10% at 11:30 AM. It again peaks at 12% at 12:30 PM before gradually decreasing to 11% at 1:30 PM and further dropping to 10% at 2:30 PM. These fluctuations indicate variation in non-linear load or harmonic-producing equipment connected to the system.

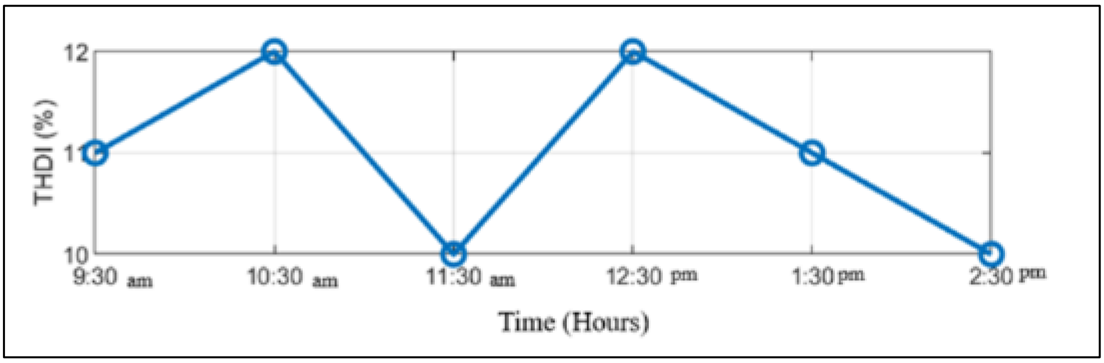

Figure 5 Total harmonic distortion in current over time

The Fig. 6, illustrates the variation of Total Demand Distortion (TDD) in Amperes (A) over time. Initially, TDD is around 720 A at 9:30 AM, then decreases to 700 A at 10:30 AM before rising sharply to 760 A at 11:30 AM. After a slight dip to 730 A at 12:30 PM, it gradually increases to 740 A at 1:30 PM and peaks at 760 A at 2:30 PM. These fluctuations indicate variation in the harmonic current demand relative to the maximum demand load. Monitoring TDD is crucial for ensuring power quality and preventing excessive distortion that could impact the efficiency and lifespan of distribution transformers.

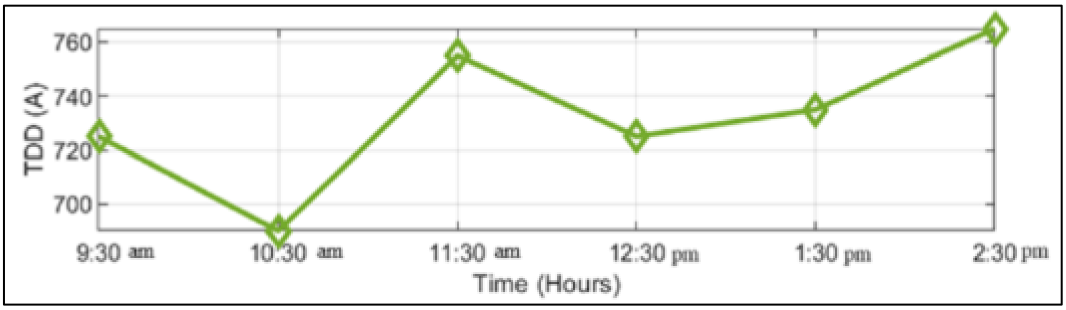

Figure 6 Total demand distortion with temperature over time

4. Conclusion

In this study presents a condition monitoring framework for distribution transformers in a solar farm environment, emphasizing the critical role of harmonic distortion analysis in assessing transformer health. By leveraging IEEE standard guidelines and real-time measurements of THD, TDD, and IHD, the research highlights the adverse impacts of non-linear loads on transformer performance, including increased losses, overheating, and insulation stress. The findings from six station transformers show that elevated THDI levels and high load percentages contribute significantly to thermal stress, with Transformers 3 and 6 showing signs of overheating, while Transformers 1, 4, and 5 exhibit current harmonic distortions beyond acceptable standard limits. These results demonstrate that regular monitoring of harmonic indices enables early detection of harmonic-related issues, facilitating timely intervention to prevent serious faults. Incorporating harmonic analysis into transformer condition monitoring not only extends the equipment lifespan but also enhances the overall reliability and power quality of distribution networks. The study underscores the necessity of continuous harmonic assessment and strict adherence to IEEE standards to ensure efficient and resilient operation of transformers within solar-based power systems.

Compliance with ethical standards

Disclosure of conflict of interest

All authors have no conflict of interest to declare.

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