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Investigation on Inverter Duty Transformer Failures at Grid Connected Solar Photovoltaic Plants: Challenges and Recommendations

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SUMMARY

The Govt of India embarked on a mission to develop 450 GW of Renewable Energy by 2030 to address the climate change problem by reducing CO_2 emissions. Even though Renewable Energy provides sustainable energy and security, it poses technical challenges to power supply reliability and quality; thus, it requires innovative and effective solutions using advanced power electronics technology. At the same time, one must address the power quality and reliability of grid-connected Solar Photovoltaic (SPV) Plants and the operational challenges in many grid-connected SPV Plants. India has installed many grid-connected SPV Plants with a total capacity of 71.145 GW of Solar PV on 31st July 2023 and contains thousands of inverter duty transformers (IDT). Recently, some of them encountered failures during the commissioning and operation due to various technical reasons despite following existing national and international standards and guidelines. However, very little information is available on the Inverter Duty Transformer (IDT) failures at national and international levels.

This technical study conducts (a) SPV plant survey and (b) Power Quality monitoring at selected SPV Plants to investigate the nature of failures, especially in the inverter duty transformer, and investigate the root cause with further studies such as modeling and analysis. Recently, CIGRE has constituted a working group A2.68 to conduct the technical study and publish the report with its findings and recommendations so that national committees can implement suggestions and revise the appropriate standards. In this paper, the authors would like to discuss both challenges and opportunities faced during this technical study, highlight the gaps present between existing standards and current practices, and provide necessary recommendations and guidelines for conducting (a) Power Quality Monitoring at the SPV Site (b) IDT failure analysis and (b) Amendments to the existing standards for the benefit of all stakeholders to reduce/prevent IDT failures at the SPV Plants. Finally, this study will benefit the CIGRE working groups, national study committees, and stakeholders to review existing practices to overcome the challenges and reduce asset and financial losses due to IDT failures in the SMART GRID.

KEYWORDS

Solar Photovoltaic Plants, Inverter Duty Transformers, Power Quality, Grid Integration, Renewable Energy, Condition Monitoring, Inter-Turn Faults, Fault Diagnosis

INTRODUCTION

Climate change initiatives have led to sudden growth in large-scale Solar Photovoltaic Generation in India since 2014. However, large-scale solar and wind energy integration requires substantial research and technical studies to address the power quality and reliability issues. Recently, there has been a concern from standards and regulatory authorities on the failure of inverter duty transformers at solar photovoltaic plants in India. However, very little information is available in the public domain on the nature of failures and the root cause of the problem. Kawamura et al. (2008) investigated failure modes of oil-immersed transformers due to static electricity, copper sulfide formation, and suppressive effect of 1, 2, 2 Benzotriazole [1], an essential phenomenon for transformer failures. A multidisciplinary team in Europe conducted a study (2012) on a large number of Inverter Duty Transformer (IDT) or Distribution Photovoltaic Transformer (DPV) failure analysis reveals the complex nature of the underlying problem and proposed (a) Site inspection (b) Electrical measurements at the site (c) Network simulations (d) manufacturing audit to identify the root cause. The investigation reveals that (i) the failure pattern is similar in all IDTs, (ii) the quality of the insulation is not satisfactory for the insulation stress due to switching transients, (iii) manufacturing quality is not suitable for acceptable performance (iv) standard and special tests conducted did not reveal any deficiency in transformer acceptance performance [2]. Cross et al. (2014) conducted forensic and failure analyses of transformers and highlighted the importance of mandatory forensic analysis for transformer failure as a policy [3].

IEEE Working Group C.159, led by Hemachandra et al. (2016), conducted a survey and proposed design consideration for DPV Transformers [4] and subsequently published a ***Guide on Transformers for Application in Distributed Photovoltaic Power Generation System, IEEE Std C57.159 (2016)*** [5]. Murray et al. (2017) highlighted the challenges and opportunities associated with grid-connected transformers in photovoltaic generation, mainly unbalanced voltage, harmonics, DC bias, and transients due to inverter and VCB switching. However, they suggest that utility and transformer manufacturers conduct simulation studies for long-term issues to understand the problems and associated challenges [6]. Fuhr et al. (2018) highlight the detection and localization of partial discharge using HFCT sensors in a transformer using time and frequency domain analysis [7]. Though the study proposes applying time and frequency domain analysis for PD localization, it has severe limitations over the time-frequency analysis, especially applying acoustic emission technique. However, industry and academic researchers have not thoroughly explored the approach until now. Chauhan et al. from Power Grid Corporation India (2020) proposed an essential solution to overcome transformer failure through an intelligent condition monitoring system for both Transformers and Reactors [8]. However, it is based on DGA using sensor data. It is important to note that DGA will not prevent Transformer failures, especially IDT. Moreover, it is an old technique, though quite helpful and used as the standard method for condition monitoring and preventive maintenance.

Randy Cox et al. (2020) proposed an innovative solution for the reliability assessment of Transformer using integrated health monitoring. It is an essential solution as reliability and asset management are crucial to implementing Smart Grid [9]. Since the proposed method uses Electrical, DGA, and Thermal data for integrated Reliability and Health Monitoring, perhaps it is an advanced technology over the previous method using DGA data alone. Simmons et al. (2020) describe an automated anomaly detection and condition monitoring system for Solar Plant Transformers using synchrophasors and is more relevant to the current study [10]. In another study, the effect of the current harmonic on distributed photovoltaic Transformer was presented [11]. In this study, the authors investigated the eddy current losses at higher harmonics and found them to be less than estimated values, allowing additional loading. Muthukumar et al. presented protection challenges and an overview of pre-synchronization in renewable energy generation in a southern regional grid in India, especially highlighting (a) tripping of wind energy due to maloperation of anti-islanding relays, (b) the presence of zero sequence voltage at PV inverter AC bus (c) protection coordination (d) maloperation of relays (e) LVRT & HVRT characteristics. These studies are essential as renewable energy penetration increases in the Indian grid, creating major outages and posing technical challenges for power systems operation. In this study, the authors highlight the need to investigate IDT failures and conduct root cause analysis to prepare necessary standards and guidelines for IDT manufacturers and SPV Plant operators.

SPV PLANT SITE SURVEY

1) Methodology

Due to a lack of information on Inverter Duty Transformer (IDT) failures at Solar Photovoltaic Plants and the remedial solutions, the International Copper Association India (ICAI) collaborated with Vellore Institute of Technology, Vellore, to perform the investigation in cooperation with various stakeholders for the mutual benefit as well as for preparing necessary guidelines and suggestion for policymakers and develop a necessary national standard. An initial survey was conducted to collect basic information on Grid-Connected Solar Photovoltaic Plants and the nature of various failures occurring on existing plants in South India, mainly to obtain data related to IDT and Inverter failures. The survey was conducted through an online Google form and on a hard copy through a site visit with the help of project collaborators Fluke India, A-Eberle India, and 4Fores India.

2) Survey Questionnaire

The objective of the survey is to engage the Solar Photovoltaic Plant Owners and Operators on the importance of the investigation into IDT failures at their SPV Plant, share relevant details, and participate in the study through NDA for a site study for mutual benefit. In addition, the survey includes the collection of the site location, and the person in charge details to plan the SPV site visit to conduct the Power Quality and Energy Audit by the VIT Team and OEMs. The survey questionnaire consists of the following:

a) SITE information and contact: Manager, Location, Capacity, Commissioning Date
b) SPV Plant Details: No of IDTs and Inverters, SPV Panels, IDT & Inverter Make, Power & Energy
c) IDT and Inverter failure details: No of failures and nature of failures
d) PQ & Energy Audit History: Regulatory requirement of PQ audit and history of PQ audit
e) Voluntary Participation: PQ Audit through NDA

Table 1: SPV Plant Survey Results

Details	SPV1	SPV2	SPV3	SPV4	**SPV5**	SPV6	SPV7	SPV8	SPV9	**SPV10**	**SPV10**	SPV11	SPV12
Rating, MW	2.3	15	2	15	20	6.2	20	15	2	3.6	NA	200	50
Commissioned	2013	2017	2016	2017	2017	2013	2016	2019	2021	2020	NA	2019	2017
Plant AGE	9	5	6	5	6	9	6	3	1	2	NA	3	5
PQ Audit	YES	YES	No	No	No	No	NA	YES	NA	NA	YES	YES	YES
IDT Failure	No	No	No	No	No	No	YES	No	No	No	YES	NO	YES
Inverter Failures	YES	YES	No	No	YES	NA	NA	No	NA	No	NA	No	NA
Cable Failures	YES	YES	No	No	No	NA	NA	YES	NA	No	NA	No	No
IGBT & PCB	No	YES	No	No	YES	NA	NA	NA	NA	No	NA	No	No
VCB Failure	No	No	No	YES	YES	NA	NA	NA	NA	No	NA	No	No
SITE Study	YES	YES	YES	YES	**DONE**	YES	YES	YES	**DONE**	**DONE**	**NA**	No	No

POSOCO Guidelines & Comments

The power system operation and control corporation issued guidelines specifying measurement of Harmonics, Flicker, and DC injection to the grid from RE plants to be within limits as described in IEEE519 standard. However, measuring these parameters once a year will not provide any information if they are within limits throughout the year. There is a high probability that they may exceed limits during regular operation for various reasons. In addition, these power quality measurements can be made mandatory for continuous real-time monitoring at all grid-connected renewable energy plants. Also, the calculation of V_{Thd} for the 40^{th} or 50^{th} harmonic is outdated and needs revision due to Supraharmonics emission from inverters. IEEE is working on developing these standards. In addition, there was no SOP available for conducting these measurements as described in CEA or POSOCO guidelines. Also, there is no provision in existing SPV Plants to conduct a PQ Audit without disturbing the plant operation of the system. Again, if the PQ limits are exceeded, then the action to be taken is not specified in the document.

PQ AUDIT AT SPV PLANTS

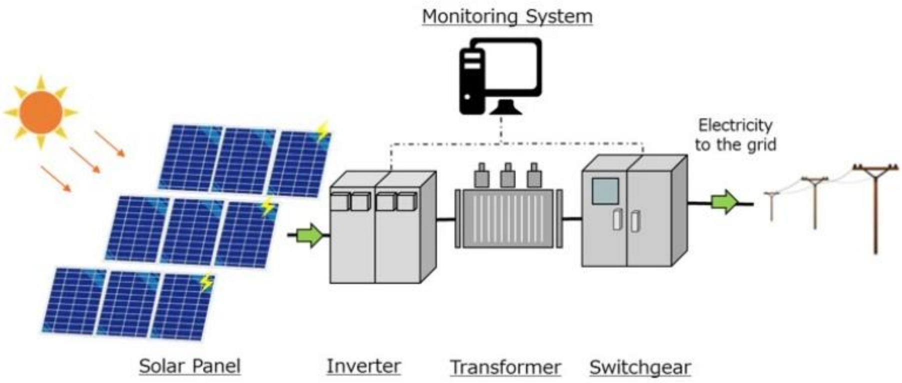

Figure 1 Power Quality Monitoring at IDT of SPV Plant

PQ Audit at SITE 1

- As per the PQ monitoring, the following observations were highlighted for further analysis:
- A total of **10001** PQ events were recorded, and the majority of them were "**Transients**" followed by "**Fast Voltage Variations**" and "**Voltage Swell"** with only one "**Voltage Dip"** during the one-week recording.
- The majority of the PQ events were "**Voltage Transients**" and occurred in **Phase A (9450)**
- A moderate number of "**Waveform Variations**" (66) and "**Voltage Swell**" (29) occurred during the monitoring period, while the "**Waveform Variations**" occurred in all three phases equally but whereas '**Voltage Swell**' occurred mainly in **Phase B (17)**
- The remaining PQ Events were **Rapid Voltage Changes** (RVC) and occurred in ALL three phases.
- Table 2 shows ONE **Voltage Dip** and 17 **Voltage Swell** recorded during the one-week monitoring period.

Table 2 Comparison of PQ Events HV Side of IDT and LV Side of IDT at Site 1

Fluke 1777 LV Side	**PQ Events**				**Fluke 434 HV Side**	**PQ Events**
	A	B	C	D		
Dips	1	1	1	1	Dips	8
Swells	7	17	5	17	Swells	0
Transients	**9450**	**275**	**102**	**0**	**Transients**	**13**
Interruptions	0	0	0	0	Interruptions	0
					Voltage Profiles	0
Rapid Voltage Changes	13	16	13	0	Rapid Voltage Changes	0
					Screens	5
					Waveforms	0
					Interval without measurements	0
Inrush Currents	0	0	0	0	Inrush Current Graphics	0
Wave Shape	22	24	20	0	Wave Events	47
					RMS Events	47

- The number of PQ Events reported on both sides of IDT Transformers by TWO different PQ Monitoring Equipment, FLUKE 435-II and FLUKE 1777, gave different results due to different instrument resolutions and features.
- FLUKE 1777 has a 1 MHz sampling frequency and hence recorded many Transients on the LV Side of IDT.
- Eight Voltage DIPS recorded on HV and Four on LV Side whereas Fourty Six Voltage Swells recorded on HV Side of IDT whereas none on LT Side. These events need to be further studied in detail as they are minor events that did not impact the SPV Site operation.

- Also, the 28 MVA IDT Transformer is Delta Connected on the 11 kV Side and Star Connected on the 380V Side.
- The significant number of Transients recorded daily is a matter of concern for further investigation. VCB and IDT failures reported at SPV Plant Sites are mainly because of Switching Transients, which may occur due to external or internal sources.
- In addition, PQ Monitoring was only done at one of the IDTs at the SPV Plant, while the site has seven 2.8 MVA IDTs and one 1.4 MVA IDT.

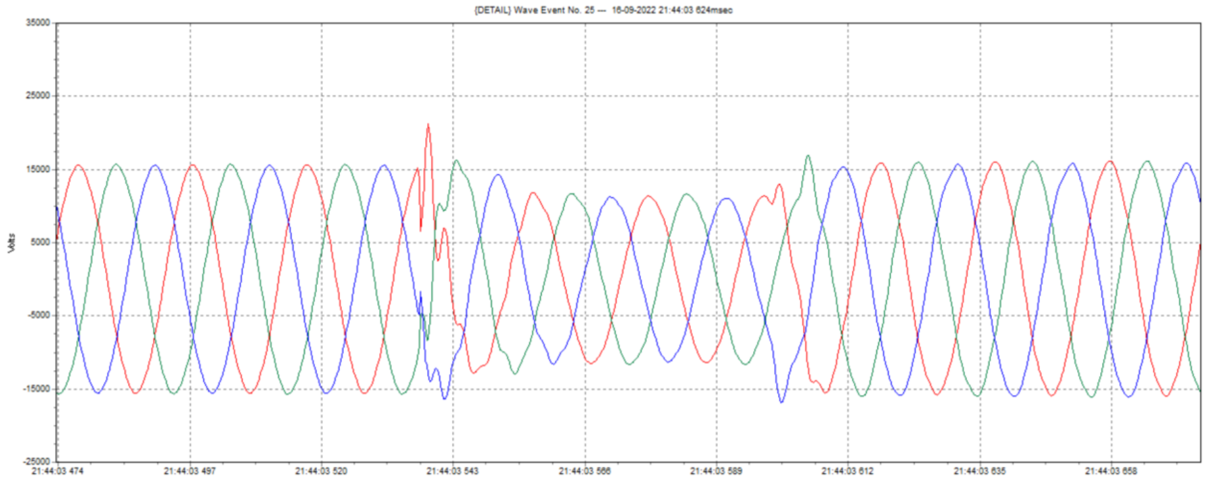

Figure 2 Simultaneous Switching Transient and Voltage Sag at SPV Site 1

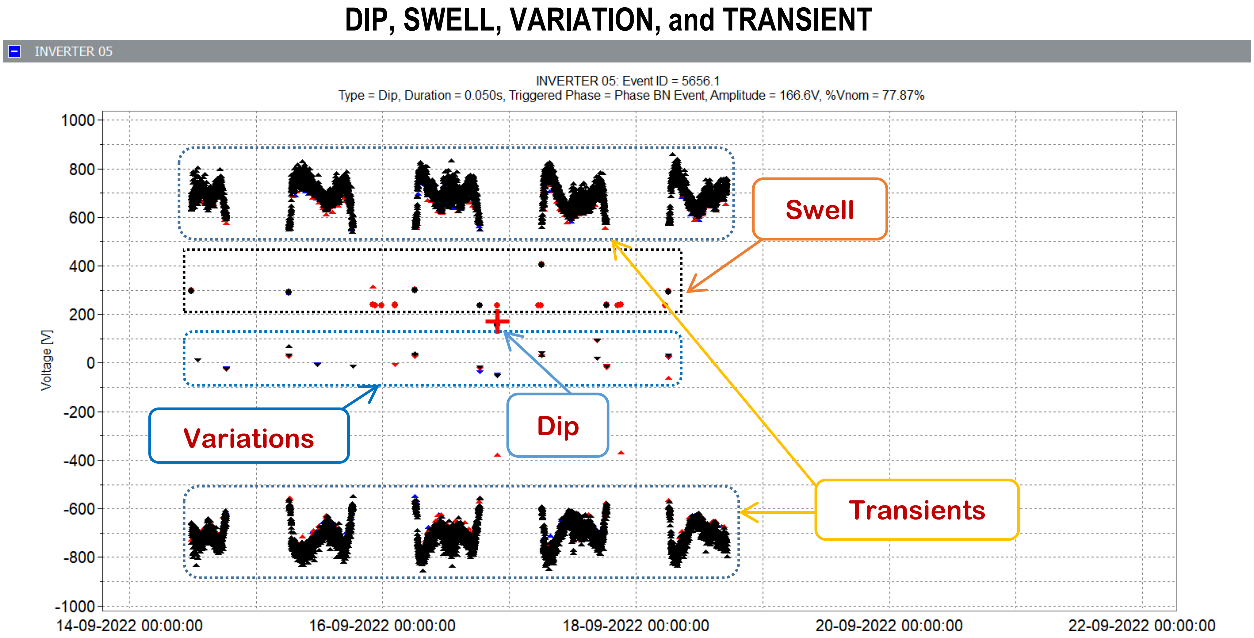

Figure 3 Power quality events recorded at SPV Site 1 on LT Side

PQ Audit at Site 2

- FLUKE 434-II is connected on both the LV and HV sides of the Inverter Duty Transformer
- As per the PQ monitoring report generated by FLUKE 434-II, the following observations were highlighted for further analysis:
- A total of **51** PQ events were recorded, as shown in Table 3, and the majority of them were "**Transients (13)**" followed by "**Voltage Dips (11)"** during the one-week recording.

- Many RMS (51) and Wave Events (51) were recorded on the HT side of IDT, whereas only one event was recorded on the LT side. In addition, no PQ Events were recorded on the LT side of IDT for unknown reasons.
- From the PQ Events plot on the ITC graph, it can be noticed that six events in Phase A, 6 Events in Phase B, and 6 Events in Phase C are separate.
- Some PQ Events recorded on the HT side will be analyzed further using Joint Time-Frequency Analysis. As this site is newly commissioned and less than six months old, little information was obtained from the Power Quality monitoring using Fluke 434-II.

Table 3 Comparison of PQ Events HV Side of IDT and LV Side of IDT at Site 2

Fluke 434 HV Side	PQ Events	Remarks	Fluke 434 LV Side	PQ Events	Remarks
Dips	11		Dips	0	
Swells	0		Swells	0	
Transients	13		Transients	0	
Interruptions	1		Interruptions	0	
Voltage Profiles	0		Voltage Profiles	0	
Rapid Voltage Changes	0		Rapid Voltage Changes	0	
Screens	13		Screens	2	
Waveforms	0		Waveforms	0	
Interval without readings	0		Interval without readings	0	
Inrush Current Graphics	0		Inrush Current Graphics	0	
Wave Events	51		Wave Events	1	
RMS Events	51		RMS Events	1	

PQ Audit at Site 3

The PQ audit at site 3 using FLUKE 434 on the LT side provides the following info:

- The number of PQ events recorded during the period 26 - 28 Dec 2022 are **97.**
- The number of PQ events recorded during the period 28th December 2022 to 2nd January 2023 are **122.**
- The number of PQ events recorded during the period 2nd January – 14th January, 2023 are **253**
- The number of PQ events recorded on the HT side during the period 2nd January – 14th January 2023 are **17869.**

There were no major technical issues during the audit period from 2nd January 2023 to 14th January 2023, despite 253 PQ events being recorded. However, on three occasions, FLUKE 1777 reset between 25th December and 2nd January 2023, perhaps due to PQ Events or some other technical glitch. When these results were compared with HT side PQ monitoring using FLUKE 1777 with FLUKE 434 on the LT side, it was observed that many PQ events that occurred on the LT side did not reflect that on the HT side as disturbance propagated towards downstream while harmonics propagate upstream. The HT side showed high harmonic content and Flicker, whereas, on the LT side, rapid changes in voltages led to harmonic distortion and transients. The critical observation for the regulators from this study is that '**Power Quality Events**' can occur outside the PQ Audit period. These disturbances depend on the location of measurement as one can note that PQ Events measured on LT and HT sides of the Inverter Duty Transformer are entirely different and can be the significant reason for equipment failure at Solar PV Plants. This study highlights that both FLUKE 434 and FLUKE 1770 provide various power quality indicators differently, and also, the location of PQ monitoring can provide a completely different view on Power Quality Performance. Thus, the critical indicator to Solar PV Plant utilities and Grid Operators is that monitoring PQ for a week at PCC does not guarantee that the Solar PV Plant meets the grid code and other regulations. If that is the case, then there will not be any grid stability or power quality issues coming from large-scale solar PV plants across the country, and it is not necessary to conduct an annual Power Quality Audit. In addition, there was no mention in the POSOCO guidelines or regulation that if the Power Quality Audit shows a large number of issues after a couple of years from the commissioning instead of at the initial stage, the necessary action should be taken by all the stakeholders. It is essential as some plants are built by one entity, operated by another, and sold to a third party. In the long run, this scenario will create technical issues for Grid Operators and Regulators.

Table 4: PQ Event Comparison on LT side and HT side of IDT at Site 3

PQ Events	26 - 28 Dec 22	28th December – 2nd January 23	2 – 14 Jan 23	Fluke 1777	Remarks
Dips	9	11	25	0	
Swells	5	1	0	**1**	
Transients	9	4	25	0	
Interruptions	2	1	0	0	
Voltage Profiles	0	0	0	0	
Rapid Voltage Changes	20	54	138	2657/2195/2036	**6188**
Screens	17	17	17	0	
Waveforms	0	0	0	1	
Interval without readings	0	0	0	0	
Inrush Current Graphics	0	0	0	0	
Wave Events	97	122	253	**183930**	
RMS Events	**97**	**122**	**253**	**17869**	

CHALLENGES & RECOMMENDATION

1) Technical Barriers

a) Obtaining prior approval from the management to conduct a PQ audit was difficult at free of cost
b) PQ audit is only done by a selected few companies.
c) There is no provision for connecting the 'PQ Analyzer' at either PCC or IDT without disconnecting the plant.
d) There was no SOP available either with the SPV Plant operator or POSOCO or CEA on the PQ audit.
e) There was no mandatory energy audit conducted at Solar PV Plants, which is essential for efficient operation through trained technical staff
f) 10% Overloading of IDT continuously for prolonged periods
g) Use of temporary external cooling to overcome the overloading issue to prolong the life of the Transformer
h) Lack of importance on monitoring switching transients and their impact on Solar PV Plant performance and inverters.
i) The POSOCO guidelines specify only monitoring of the following (Harmonics, Flicker, and DC injection): Voltage (THD, Individual distortion, Flicker), Current (TDD, Individual component, DC component.

2. Recommendations

However, it is essential to recommend the following suggestions for inclusion in the revised CEA guidelines:

a) Explicit provision for connecting PQ Analyzer at PCC and both sides of grid-connected Power Transformer (not IDT)
b) Provision to connect PQ Analyzer on both sides of Inverter Duty Transformer (IDT)
c) Measuring Supraharmonics emanating from the Solar PV String Inverter and Central Inverter using the latest Power Quality Analyzer (Fluke 1770/ PQ Box)
d) Mandatory requirement for real-time monitoring of PQ Analyzer at Solar PV plants
e) Implementing the solution to operate most efficiently is mandatory for an Energy Audit.
f) Recording of SPV Plant equipment failure for developing diagnostic solutions for enhanced life of equipment and plant is necessary for the SMART GRID.

g) Mandatory requirement of Power Quality Monitoring and Analysis and providing training for all Solar PV Plant operators and managers is essential for the efficiency and reliability of the operation of Renewable Energy Generation.
h) Conducting both PQ and Energy Efficiency audits to benchmark performance and carbon emission reduction is mandatory.

CONCLUSIONS

This paper highlights the importance of investigating the failure of inverter duty transformers (IDT) and inverters (string & central) as the renewable energy integration into the electric grid increasing, creating technical challenges for power system reliable and efficient operation. In addition, there is a need for continuous monitoring of power quality to identify the root cause of failures at renewable energy plants, both at solar and wind. Earlier studies identified the design and manufacturing quality of IDT as one of the reason for failures. This study found that switching transients could be the significant reason for inverter duty transformer winding, components, and VCB failures. However, no investigation or data is available to conclude the same due to the lack of power quality monitoring at large grid-connected Solar Photovoltaic Plants in India. In addition, there is also a lack of power quality expertise to address these problems and take necessary preventive action by utilities. Hence, this technical study highlighted challenges and opportunities to address the IDT failure problem at SPV Plants and give appropriate recommendations for possible implementation by regulatory authorities.

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APPENDIX

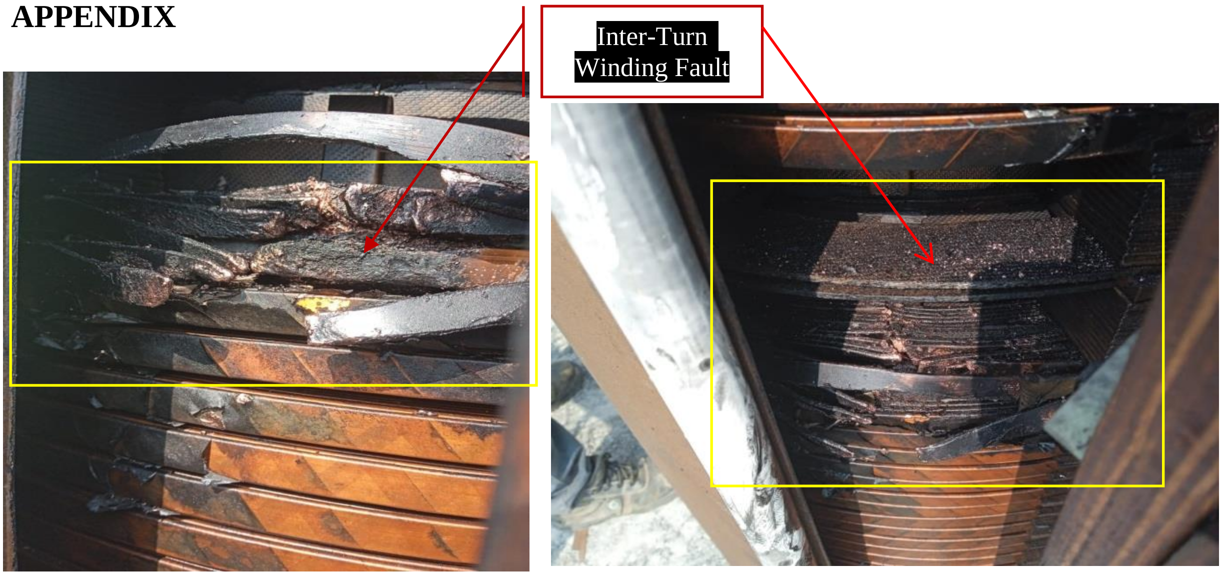

Figure 4(a) Inter-turn Fault of 1-Phase of 12.5 MVA Inverter Duty Transformer (b) Damaged Winding

Figure 4(c) 12.5 MVA Inverter Duty Transformer Failure