Assessing the Impact of Harmonics On Distribution Transformer Having Solar Rooftop PV Installations

Mr. S.P. Rathod
Gujarat Power Research & Development Cell
Gujarat Urja Vikas Nigam Limited
IIT Gandhinagar, Gujarat, India
sprathod.guvnlrnd@gmail.com

Mr. H.M.Sakariya
Gujarat Power Research & Development Cell
Gujarat Urja Vikas Nigam Limited
IIT Gandhinagar, Gujarat, India
hmsakariya.guvnlrnd@gmail.com

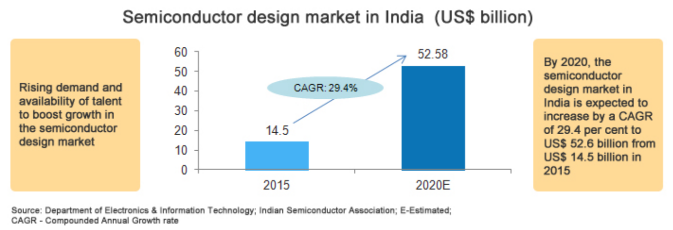
Mr. J. B. Upadhyay
Gujarat Power Research & Development Cell
Gujarat Urja Vikas Nigam Limited
IIT Gandhinagar, Gujarat, India
jbupadhyay.guvnlrnd@gmail.com

***Abstract*— Due to abundant usage of non-linear loads and the acceptance of distributed generation resources specifically Solar PV installations, it is obvious that the harmonics contents in the electric power system shall get increased.. This increased contents of harmonics pollute the power quality of the system and cause problems to the end-users. Not only that, but it is also causing the derating of the assets of the distribution utility specifically distribution transformers and financial implications in terms of losses. Due to technological advancement in electronics technology and competition in the power electronics market, the impact of harmonics is going to cause increased pain to the utility function as the time progresses. If this issue is not been addressed at present, it will become a huge challenge for the utility to address the power quality issues in coming days.., this paper describes the collection and analysis of various relevant field data results taken for various type of loads in the power system and thereby calculating its impact on the distribution transformer.**

Keywords—Nonlinear devices, Harmonics, DT-Distribution Transformer

I. INTRODUCTION

The market of a semiconductor device in India is thriving. From the below figure, it can be concluded that there is a progressive rise and shall result in a steep rise in the percentage demand of the nonlinear devices in the forthcoming years in India. In the absence of any penalty on consumers by using nonlinear electrical load and thereby deteriorates the quality of power system and also due to increased competition in the electronics market, the producers of electronics industries are less concern about the issue of harmonics by providing filters in their products. The other source of harmonic generation in the power system is the increasing usage of renewable energy generation sources, the converter - inverter alike electronics devices are increasing at a rapid rate. Due to the above two reasons, the power quality shall be the prime concern; which is to be addressed by power distribution utility.



A. *Solar rooftop in India:-*

The government of India has set up an aggressive target of 175 GW of renewable generation by 2022. Out of which 40 GW of the target is set to be achieved by rooftop PV installation by 2022. To achieve the target set by GoI, the government has also announced a reasonable amount of subsidy, which makes the rooftop model quite acceptable, especially for residential consumers. The inverter is the heart of the Solar PV system and in the case of inferior quality of the inverters make the device quite nonlinear type. In the absence of any strict provisions of penalty on harmonics generation, and other power quality-related parameters by state regulatory commission, the power quality issue is raising day by day. The existing consumer tariff meters provided by the utility are also not designed with the provision for measuring harmonic contents in the consumer loading.

In addition, in the PV rooftop installation, the power factor of the inverter is kept at unity because of Kwh based billing and not the KVAH based billing. In such a case, the reactive power requirement of the load is provided by the grid. In this scenario, during the peak sun hours, the active power demand is likely to reduce due to PV generation whereas the reactive power drawn from the grid is likely to remain constant. This again imposes challenges to the grid stability.

Solar rooftop affects the power factor in two ways. As the reactive power requirement from the grid is increased due to the operation of the solar rooftop inverter at unity power factor. the displacement power factor reduces. Secondly, due to the increased current harmonics component, the distortion power factor component also increases. These both combined effects make the true power factor deteriorates.. Consequently, this causes further damage to the resultant power factor and also affect the reactive power flow from the grid.

In the conversion from DC waveform to match with grid AC waveform, the non-linearity of the inverter causes injection of harmonic components into the AC waveform. These current harmonics causes increases in voltage harmonics. The increase in harmonics can cause the following effect at the distribution transformer level

1. Effects of Harmonics on Load Losses
2. Derating of transformer
3. Effect of PV Penetration on power factor
4. Effects of Uneven Distribution of PV system on Distribution Transformer
5. Effect on Top oil rise

B. *CASE STUDY (200 KVA Distribution Transformer)*

To evaluate effects of harmonics on distribution transformer with connected solar rooftop installations connections, The harmonic analyzer i.e. Power quality meter No: PM2230 of M/S Schneider electric installed on LT Side of selected one 200 KVA Transformer Center at Vasana subdivision of Madhya Gujarat Vij Company Limited.

The consumer statics connected on this distribution transformer is as below

Consumers Category	Residential
No. of consumers	40
Total Contacted Load	283 KW
Solar rooftop Consumers	6 Nos
Total Installed SPV capacity	33 KW

Table-1

The harmonic analyzer is equipped with IoT base remote data acquisition facility which is configured for capturing and transmitting data at every 5 minutes interval. The detail of the distribution transformer, on which the harmonic analyzer is installed is as below.

Sr. No.	Parameters	Values
1	DT Rating (KVA) - Connected	200 KVA
2	Transformer Ratio	11/0.433 KV
3	No Load Loss (Watt)	106.7 watt
4	LV side DC resistance at ambient temp (ohm)	0.035425 Ω
5	Total Load Loss (Watt) at 75°C	2013.68 watt
6	Total I2R Loss (Watt) at 75°C	1920.99 watt

Table-2

Transformer losses are categorized in two main categories, No Load Loss, and Total Load loss

$$P_T = P_{NL} + P_{LL} \qquad (1)$$

Where, P_T = Total loss (watts)

P_{NL} = No-load loss or Core loss (watts)

PLL = Total Load loss (watts)

No-load loss is due to the magnetizing current needed to energize the core of the transformer. Load loss consists of I^2R and stray losses. Stray loss can be defined as the loss due to stray electromagnetic flux in the windings, core, core clamps, magnetic shields, enclosure or tank walls. Thus, the stray loss is subdivided into winding stray loss and stray loss in components other than the windings (P_{OSL}) viz. frames, flitch plate, and tank. The winding stray loss comprises of winding conductor strand eddy-current loss and loss because of circulating currents between strands or parallel winding circuits. The total load loss can express as follows in Equation (2)

$$P_{LL} = P + P_{WEC} + P_{OSL} \qquad (2)$$

Where

P_{LL} is the Total load loss (watts)

P is the I^2R loss portion of the load loss (watts)

P_{WEC} is the winding eddy-current loss (watts)

P_{OSL} is the other stray loss (watts)

1. *Effects of Harmonics on Load Losses*

Due to harmonics components, rms value of the load current is increased, the I^2R loss will be increased accordingly. The rms value of the nonsinusoidal load current can be expressed as follows in Equation

$$I_{rms} = \sqrt{\sum_{h=1}^{h=h_{max}} I_h^2} \qquad (3)$$

Irms is the rms load current (amperes)

h is the harmonic order

hmax is the highest significant harmonic number

I_h is the rms current at harmonic h (amperes)

Eddy Current Losses in windings

Skin effect and proximity effect are most important phenomena which cause Eddy current losses in the transformer. In the transformer, internal winding placed adjacent to the core so eddy current losses in the internal winding are higher than External winding, due to the concentration of electromagnetic flux intensity near the core that covers these windings. Winding eddy current loss as per IEEE C57110.2018 can express as follows in the Equation.

$$P_{EC} = P_{EC-O} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^2 \qquad (4)$$

Where, P_{EC} is the winding eddy-current loss (watts)

$P_{EC\text{-}O}$ is the winding eddy-current loss at measure current and power frequency (watts)

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic h (amperes)

I is the rms load current (Ampere)

To determine the capability of a transformer to cater to the nonlinear load, the increase in winding eddy current losses due to harmonics has to be considered. F_{HL} is a proportionality factor applied to the winding eddy losses, which represents the effective rms heating as a result of the harmonic load current. F_{HL} is the ratio of the total winding eddy current losses due to the harmonics, P_{EC}, to the winding eddy current losses at the power frequency, when no harmonic currents exist (P_{EC-O}).

$$F_{HL} = \frac{P_{EC}}{P_{EC-O}} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \qquad (5)$$

Where,

F_{HL} is the harmonic loss factor for winding eddy currents
h is the harmonic order
h_{max} is the highest significant harmonic number
I_h is the rms current at harmonic h (amperes)
I_1 is the rms fundamental load current (amperes)

Harmonic current effect on other stray loss

Other stray loss in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current and the harmonic frequency to the 0.8 exponential power, as stated in below equation.

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_R} \right)^2 h^{0.8} \quad (6)$$

Where,

P_{OSL} is the other stray loss (watts)

$P_{OSL\ R}$ - is the other stray loss under rated conditions (watts)
h is the harmonic order
h_{max} is the highest significant harmonic number
I_h is the rms current at harmonic h (amperes)
I_R is the rms fundamental current under rated frequency and rated load conditions (amperes)
The Harmonics loss factor for other stray losses can be expressed as follows in equation

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1} \right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1} \right]^2} \quad (7)$$

F_{HL-STR} is the harmonic loss factor for other stray losses

Calculation of Load Losses Due to harmonics for 200 KVA Transformer

To evaluate the effects of Harmonics on DT having Solar PV penetration, power quality analyzer with real-time data acquisition and monitoring facility was installed and monitored for the period of 56 days. The average values of electric parameters and harmonics are as tabulated below.

Average Load rms Ampere	60.58
Average THD (%)	30.42
Average DT loading (KVA)	44.17
200 KVA Average loading (%)	22.09
Fundamental Ampere	57.96

Table-3

Value of Measured Individual Harmonics and normalized to fundamental load current as below

Harmonic order(h)	Magnitude (%)	(I_h/I_1)
1	100	1.000
3	26.03	0.260
5	9.62	0.096
7	7.22	0.072
9	3.79	0.038
11	2.24	0.022
13	1.55	0.016
15	1.52	0.015
17	1.19	0.012
19	1.22	0.012
21	0.50	0.005
23	0.75	0.008

Table-4

The calculations are tabulated in Table -5 as below

h	$(I_h/I_1)^2$	h^2	$(I_h/I_1)^2 * h^2$	$h^{0.8}$	$(Ih/I1)2 * h^{0.8}$
1	1.000000	1	1	1.00	1.000000
3	0.067740	9	0.60966065	2.41	0.163133
5	0.009264	25	0.231595815	3.62	0.033571
7	0.005211	49	0.25531905	4.74	0.024715
9	0.001438	81	0.116474038	5.80	0.008339
11	0.000501	121	0.060596444	6.81	0.003410
13	0.000242	169	0.040833723	7.78	0.001881
15	0.000232	225	0.052180551	8.73	0.002024
17	0.000141	289	0.040743727	9.65	0.001360
19	0.000149	361	0.053657895	10.54	0.001567
21	0.000025	441	0.010975073	11.42	0.000284
23	0.000056	529	0.029820448	12.29	0.000693
∑	1.085		2.502		1.241

Table-5

The summation of the values of the second column of Table-5, $(I_h / I_1)^2$ =1.085 which represents the rated rms fundamental load on a per-unit basis. The harmonic loss factor for this harmonic distribution using Equation (5) is as follows

$$F_{HL} = \frac{2.502}{1.085} = 2.306$$

The summation of the values of the sixth column of Table-5 divided by the summation of the second column of table-5 results in a harmonic loss factor for other stray losses as per equation (7) is as follows

$$F_{HL-STR} = \frac{1.241}{1.085} = 1.144$$

The summation of the values of the second column is 1.085. and the square root of this value is 1.046 which is the per-unit rms current The rms current corrected for the 22.09 % load results in the following multiplier to determine losses at the specified load conditions,

P_{LL} (pu) = $(1.0416)^2 * (0.2209)^2 = 0.0529$

for rated load P_{LL}(pu) = $(1.0416)^2 * 1 = 1.085$

Where P_{LL} (pu) is the per-unit load loss

For 200 KVA Losses under Linear and Non-Linear load Calculated as the following table

Type of Loss	Rated Loss (W)	Load Loss at 22.09% Loading (W)	Harmonics Multiplier	Corrected Loss at rated Load	Corrected Loss at 22.09 % Loading
No Load	106.70	106.70		106.7	106.7
I2R	1920.99	101.62		2084.27	101.62
Winding Eddy	55.61	2.94	2.306	139.15	6.78
Other Stray	37.08	1.96	1.144	46.02	2.24
Total Losses	2120.38	213.22		2376.14	217.35
Increse in Loss (W)				**255.76**	**4.12**
Increse in Loss (%)				**12.06%**	**1.93%**

Table-6

Table 6 shows the relation between increase in the load/generation with high harmonic content with the increase in the percentage loss of distribution transformer for actual loading and rated load conditions. As shown in table-6, the increase in loss due to harmonic content is 12.06 % and 1.93 % at 44.17 KVA (i.e. 22.09%) average load during PV Generation duration. This increase in losses is the result of a significant increase in rms value of the load current and eddy current losses in winding which further increases the heat generation in winding and reduces the capacity of the transformer to its rated KVA.

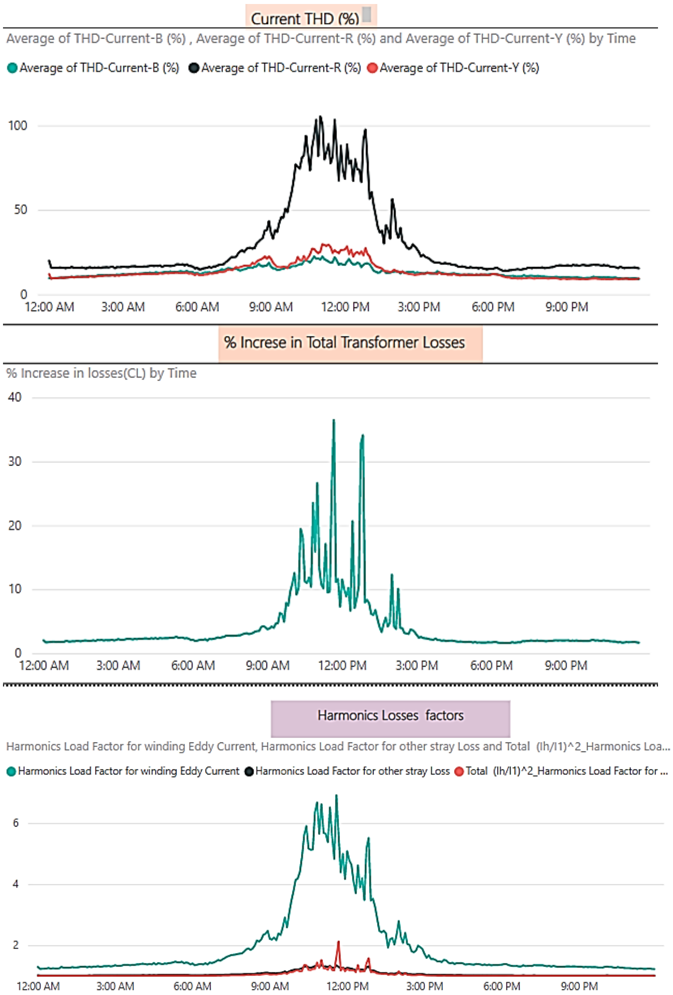


Figure-1

Fig.1 shows the aggregate average statistics plotted on power Bi tools to graphically represent the total losses of transformer and Harmonics losses factor increases as the value of a Current harmonic varies throughout the study period (56 days). It is concluded that during PV generation duration fundamental value of current reduced at Transformer level which magnifies THD value of current and also solar inverter harmonics added into the network which makes the scenario worse than before.

2. *Effect* of Harmonics on Derating of Transformer

The maximum permissible nonsinusoidal load current with given Harmonic composition as per IEEE C57.100 can express as follows in Equation

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

I_{max} (pu) is the max permissible rms nonsinusoidal load current under rated conditions

P_{LL-R} (pu) is the per-unit load loss under rated conditions

F_{HL} is the harmonic loss factor for winding eddy currents

P_{EC-R} (pu) is the per-unit winding eddy-current loss under rated conditions can be expressed as follows 200 KVA Transformer.

$$P_{\text{EC-R}}(\text{pu}) = \frac{0.55 \times 4 \times P_{\text{EC-R}}}{K \times (I_{2\text{-R}})^2 \times R_2}$$

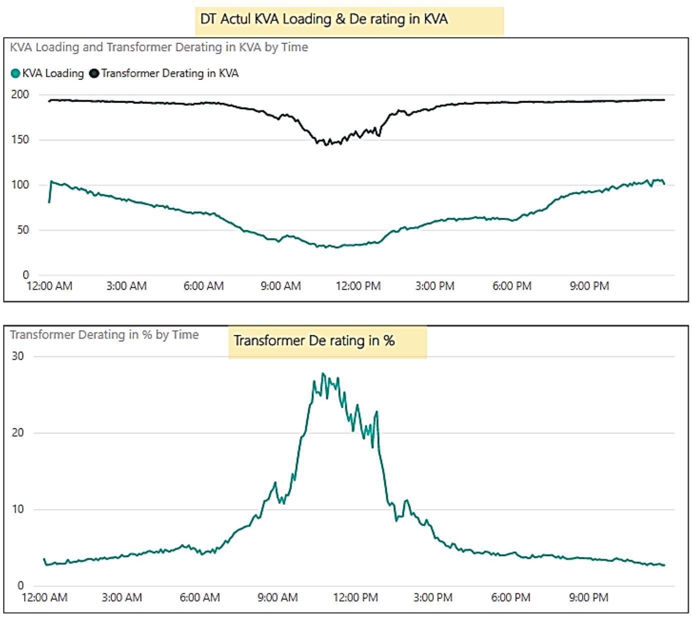


Figure-2

Increase in the PV generation will increase the harmonics content of the transformer which in turn will deteriorate the transformer rating. The Figure-2 here shows that how the increase PV Generation will de-rate the transformer.

However, this issue is particularly cause problem when the transformer is heavily loaded during solar hours and solar generation is quite low, which is rarely the case. More often, on a fairly constant load pattern, due to the increase in the generation during sun hours, the load on the transformer goes down. Hence, the transformer would rarely be in a position to be overloaded, even after considering the Derating due to harmonics.

3. Effect of PV Penetration on powerfactor:-

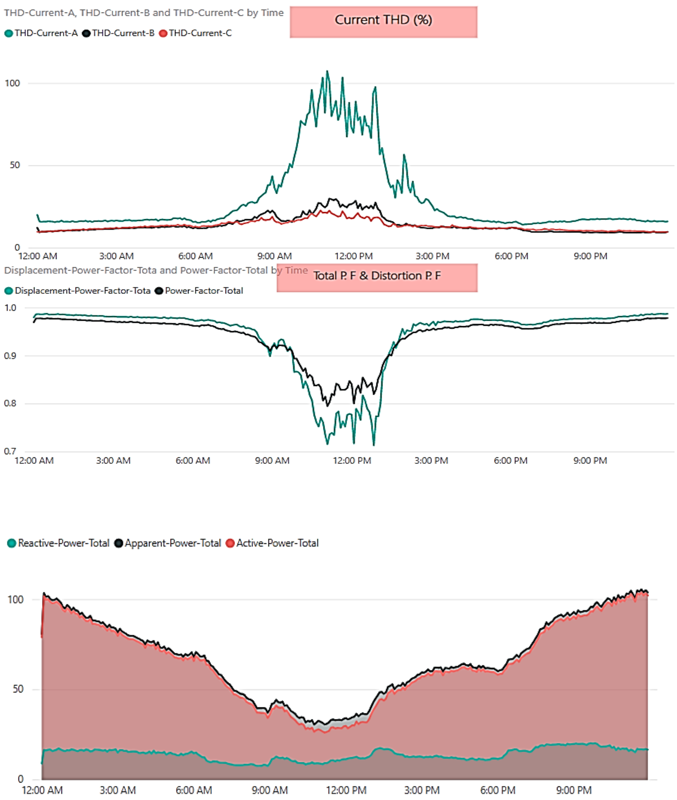


Figure -3

The effect of harmonics on the power factor is often not considered which majorly impacts the power quality parameters. During the solar period, there are following two reasons which contribute towards the lower PF at Distribution Transformer Level.

1. During the solar period, PVs are contributing towards reducing the active power, whereas reactive power remains fairly constant as mostly solar Inverters set for unity power factor which means that PV generators aren't contributing towards reactive power and all required reactive power are supplied through the grid which is evident on the metering of the transformer.

2. Due to the high content of harmonics, the distortion power factor tends to raise, which was otherwise fairly following the true power factor.

True P.F = Displacement P.F * Distortion PF

$$\cos\emptyset\,(T) = \cos\emptyset\,(Disp) * \cos\emptyset\,(Dist)$$

Effect on power factor due to harmonics and PV penetration effect is evident on the power factor.

4. Effects of Uneven Distribution of PV system on Distribution Transformer

Majority of Solar rooftop installations are single phase-type. The phase-wise uneven distribution of PV rooftop in LT Distribution network is a major reason which causes unbalance loading of Transformer. This ultimately results in to the excessive neutral current. Hence, before releasing new solar rooftop PV system proper planning shall be carried out to avoid unbalancing of Transformer loading. Figure 4 shows how improper distribution of load on transformer center results in excessive neutral current during solar generation Duration.

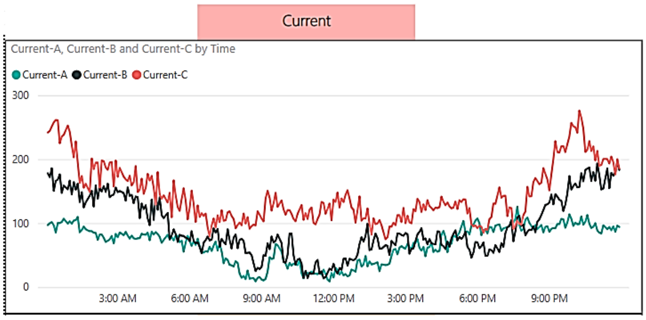


Figure- 4

5. Effect on Top Oil Temperature

When the SPV systems (or nonlinear loads) are connected at transformers it increases Skin effect and total losses as discussed earlier. This results in to extra heating of transformer winding and oil which ultimately leads to early transformer insulation failure.

However, PV Generation reduces the loading of the Transformer. Furthermore, In Gujarat state maximum 65% of PV Penetration allowed of the capacity of the Distribution transformer. Hence, the load losses of the transformer reduce and transformer would be in a position to be overloaded even after considering the effects of Harmonics.

II. CONCLUSION

It is evident from the real on-field study conducted that the harmonics is going to spoil the scenario of the power system sooner or later. If not properly managed, the same is going to deteriorate the asset of power utilities and also affect the consumer by damaging their equipment or worse. The paper just describes one side of the harmonics i.e. impact on the utility asset, especially transformer. There are many papers available which shows the impact of harmonics on various electrical equipment and consumer appliances, that side is also be needed to be considered. Furthermore, in the foreseeable future, it is anticipated that the utility would expect the PV Solar Inverter to support the power system with ancillary activities (e.g. power factor correction, reactive power support, etc.) apart from injecting active power into the grid.

It is much important that awareness to the monitoring of harmonics and other power quality related parameters needed to be increase amongst the power utility. In a stage, where power utility has recently transited from the electromechanical meters to static meters and now static to the smart meters, another anticipated transition after a few years from smart meters to smart meters with power quality measuring facility parameters will likely to increase the financial crunch of the DISCOMs. It is very important that the standardizing committee include this into the tariff meter specification and regulatory body make it mandatory so that DISCOMs may find it convenient to implement.

References

[1] IEEE C57.110-2018, IEEE Recommended Practice for Establishing Liquid Immersed and Dry-Type Power and Distribution Transformer Capability when Supplying Nonsinusoidal Load Currents

[2] Jaspreetsingh, sanjeev Singh, Amanpreetsing, Effect of Harmonics on Distribution Transformer Losses and Capacity.

[3] Dejan Pejovskia, Krste Najdenkoskib, Mihail Digalovsk, Impact of different harmonic loads on distribution transformers

[4] Mahrous A. Taher, Salah Kamel, and Ziad M. Ali K-Factor and Transformer Losses Calculations under Harmonics

[5] Dr. Abla GADO Eng. Hassan ABO GAD Eng. Salah RADWAN, EFFECT OF TYPES OF LOADS IN RATING OF TRANSFORMERS SUPPLYING HARMONIC-RICH LOADS

Author: Biodata

Sh. S.P.Rathod (Gujarat Power Research and Development Cell, GUVNL, IIT Gandhinagar) - B.E. Electrical

He is currently working as an R&D Engineer at GPRD Cell, GUVNL. He has in total six years of experience. In the initiation of the carrier he has served a Welspun Corp as a junior engineer for around 1 year in which he worked in areas of Level-1 Automation, Drives, Field sensors, SCADA and automation system troubleshooting activities. Then, he has joined UGVCL in which he was assigned the role of O&M Junior engineer overseeing operation and maintenance activity of power distribution lines, Transformers, energy meters etc. Also, Overseeing various Power quality and Reliability issues related to Power distribution system and Consumers. Then he was selected at GPRD cell, GUVNL through internal recruitment in which he was assigned the role of R&D Engineer in which he has done research in field of Various Power quality related issues of DISCOMs, automation and SCADA of Distribution system, Development of metering scheme for Grid connected Agriculture consumers having solar installations, Renewable Energy projects, Smart feeder monitoring system and Development of Onsite CTPT Unit testing facility etc.

Sh. H.M.Sakariya (Gujarat Power Research and Development Cell, GUVNL, IIT Gandhinagar) - B.E. Electrical, ACPDM

He is currently working as an R&D Engineer at GPRD Cell, GUVNL. He has in total seven years of experience. In the initiation of the carrier he has served an ERDA as an assistant engineer for around 3 years in which he worked in areas of Product Testing & Inspection, Condition monitoring, Fault Diagnostics, Calibration & Quality Management, Energy Audit of various electrical apparatus. Then, he has joined PGVCL in which he was assigned the role of Lab testing engineer overseeing operation of testing of various kind of Meters, CT PT unit, etc. Then he was selected at GPRD cell, GUVNL through internal recruitment in which he was assigned the role of R&D Engineer in which he has done research in field of Various Power quality related issues of DISCOMs, Meter communications through LoRa WAN, Renewable Energy projects, Battery Energy Storage Systems (BESS), Improvement of safety by earthing systems, etc.

Sh. Jatin B Upadhyay (Gujarat Power Research and Development Cell, GUVNL, IIT Gandhinagar) – MBA (Finance), B.E (Electrical), ACPDM

He is currently working as an R&D Engineer at GPRD Cell, GUVNL. He has in total 20 years of operational and managerial experience in the power distribution at various stages. He joined PGVCL in the year 1998, in which he was assigned the role of Operation and Maintenance engineer at sub division level. After promoting to next carder in the year 2008, he has the experience of New HT/EHT consumer activities, HT consumer installation testing, Lab testing, power system improvement, various scheme implementation and monitoring, Energy audit at distribution feeder level, substation level etc. Since, April-2017, he selected at GPRD cell, GUVNL through internal recruitment in which he was assigned the role of R&D Engineer where he has been working on the various research base projects for power quality issues like Harmonics, Over and under voltage at MV feeder level, Reactive Power requirement of power grid, Distributed RE Solar PV base generation scheme and its monitoring tool, Accurate testing of HT/EHT consumer metering, Substation automation and Feeder level interruption monitoring system etc.