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Effect of Generated Harmonics On Transformer Losses Due to Solar Penetration

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Abstract
Transformers are the essential component in transferring large amounts of power, and they are often designed and engineered to operate with rated frequency and perfect sinusoidal input supply. When a transformer is fed from the output of a solar PV inverter, its efficiency decreases or harmonic losses increase. A collection of current harmonics data extracted from inverter output as a working explanation of a specific harmonic for analytically assessing transformer losses. This paper examines the increase in the losses generated with and without consideration of even current harmonics of the PV inverter using the Matlab program for Transformers due to the impact of solar inverter output penetration into the grid.
Keywords*:* *Harmonics, Transformer Losses, PV Inverter, PV module.*

1. Introduction

Solar PV injection fig.1, is one more cause of harmonics injection for an increase in losses in a transformer in addition to types of equipment including EV chargers, Melting furnaces, gas discharge lamps, converter drives [1-3], UPS systems, and the increasing computer power supply[3]. Harmonics of a waveform are components whose frequencies are multiple integers of a 50 Hz or 60 Hz fundamental wave. 100 Hz, 150 Hz, 200 Hz, and 250 Hz are the 2nd, 3rd, 4th, and 5th are multiple or harmonic components of a 50 Hz fundamental waveform. Harmonic distortion is usually caused by nonlinear devices in electric power systems (Awadallah Mohamed A T. X., 2016) . Increase in oil temperature pose a risk to overheating of transformers. Due to high rate of solar energy utilization in recent years, there has been an increased concern about the effects of solar PV injection in the electric power system [4]. This leads to voltage or current distortions beyond the criteria specified in the IEEE-519 or IEEE1547 standards, thereby limiting the amount of PV penetration on the circuit [5-7]. Inverters as solid-state devices are major sources of harmonics. The harmonic current is injected from the inverters to the distribution circuit potentially affecting customers connected to the same circuit. Harmonic currents adversely affect virtually every component in the power system, creating additional dielectric, thermal, and/or mechanical stresses (Agus Ulinuha, 2021) ICETIA [8].

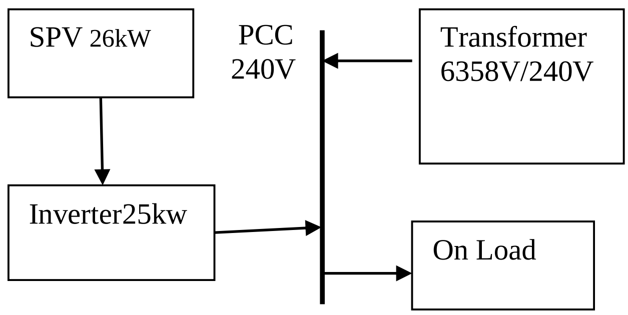

Figure 1 Solar PV injection

1.1. Undesired Effect of Current Harmonics of PV Inverter On Single-Phase Transformer

- **Transformer's R.M.S:** Harmonic currents may cause the transformer's r.m.s to exceed its capacity if it is exclusively sized for the kVA requirements of the load [9].
- **Eddy-current losses** are currents that are induced by magnetic fluxes in a transformer. increase with increase harmonic frequency.
- **Core losses:** The impact of harmonics on the

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applied voltage and the transformer core design will determine the rise in nonlinear core losses in the presence of harmonics. (Das, (2018))

The predicted lifetime will be shortened as a result of the aberrant temperature rises brought on by harmonic currents, which will increase losses. Such circumstances necessitate either upgrading with alarger and costlier unit or transformer derating to restore to the usual life expectancy (Figure 2) AC output current is distorted due to the solar inverter generated harmonics [10-13]. For analysis purposes, particularly where the harmonics from a specific PV unit are not available, Table 1 is used to represent a case of current distorted more than 5% (Cardona, 2005).

1.2.Separation of Transformer losses (Load Losses, No-Load Losses, Core Losses)

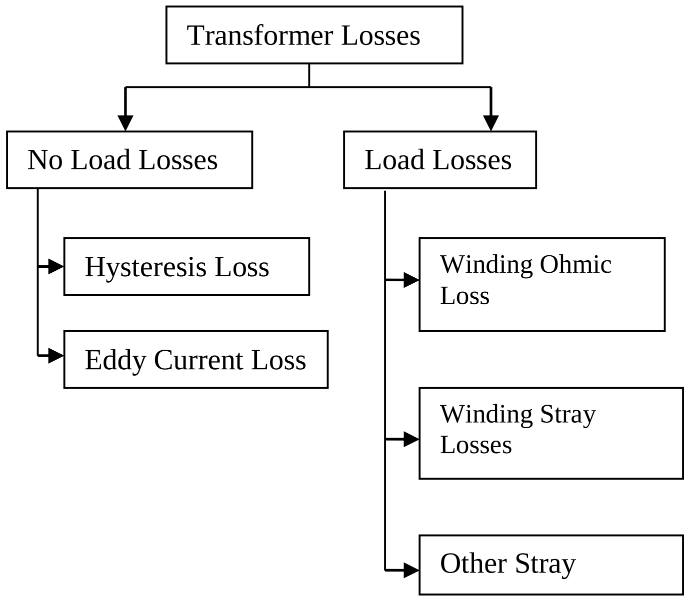

Figure 2 Transformer Losses

This can be expressed in the equation:

- P_{nl} is the no-load losses
- P_{ll} is the load losses
- P_T is the total losses

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

$$PLL = Pdc + Pec + Posl \quad (2)$$

Table 1 Current Harmonics Present in Inverter Output

h	Mag.P.U (I_h/I_1)
1	1
2	.01124
3	.03255
4	.00261
5	.03466
6	.00124
7	.01118
8	.000815
9	.0484
10	.00838
11	.00669
12	.00793
13	.00454
14	.01057
15	.00303
16	.005
17	.01474
18	.00584
19	.01132
20	.00709
21	.00496
22	.00396
23	.00208
24	.00352
25	.01328
26	.00192
27	.00608
28	.01194
29	.00893
30	.00671
%THD	6.27%

- P_{ohmic} or P_{dc} is the power loss due to load current and DC winding resistance [14].
- Pec is the winding eddy losses.

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- Posl is the other stray loss concern with clamps, tanks, etc.
- I_h is the fraction of total rms load current at harmonic number h [15].
- If Pe_f is the eddy current loss at the fundamental frequency f given by equation 3:

$$Pef = I_1^2 h^2 \quad (3)$$

Pe_h is the eddy current loss at harmonic number h,

$$Pe_h = Pef\ I_h^2 h^2 \quad (4)$$

The distribution of eddy-current loss and other stray losses between the windings is assumed according to the guideline in C57.110-2018 - IEEE for oil filled transformer [16-19].

2. Effect of Harmonics on Other Stray Losses

The other stray losses are assumed to vary with the square of the rms current and the harmonic with reference to [20-24].

- It is distributed 60% in the low voltage winding and 40% in the high voltage winding if maxium current rating less than 1000 A (regardless of turns ratio) for all Transformer.
- Above criteria of loss distribution also define for Transformer of turns ratio of 4:1 or less.
- Distribution of losses 70% contribution of low voltage; winding and 30% of high voltage winding for all transformers having a turns ratiogreaterthan4:1 and also having one or more windings with a maximum self-cooled current rating greater than 1000 a (Hussein I. Zynal [25-29].

2.1. Impact of Harmonics on DC Losses

These losses will rise with the square of the current if harmonic components cause the RMS value of the load current to rise [30-34].

$$P_\Omega = R_{dc} \times I_R^2 \quad (5)$$

$$P_\Omega = Rdc \times \left(\sum_{h=1}^{h=\max} I^2_{h,rms} \right) \quad (6)$$

2.2. Harmonic Loss Factor for Winding Eddy Currents

The eddy current losses generated by the electromagnetic flux are assumed to vary with the square of the frequency and square of the RMS current and the [35]: (Das, (2018)..)

$$Pec = Pec-R \sum_{h=1}^{h=\max} h^2 \left(\frac{I_h}{I_1}\right)^2 \quad (7)$$

$$F_{HL} = \frac{\sum_{h=1}^{h=\max} h^2 \left(\frac{I_h}{I_1}\right)^2}{\sum_{h=1}^{h=\max} \left(\frac{I_h}{I_1}\right)^2} \quad (8)$$

2.3. Harmonic Loss Factor for Other Stray Losses

According [36-39] other stray losses are assumed to vary with harmonic frequency to the power of 0.8 and the square of the r.m.s current calculation in Table 3.

$$P_{osl} = P_{osl-R} \sum_{h=1}^{h=\max} h^{0.8} \left(\frac{I_h}{I_1}\right)^2 \quad (9)$$

$$F_{HL-STR} = \frac{P_{osl}}{P_{osl-R}} = \frac{\sum_{h=1}^{h=\max} h^{0.8} \left(\frac{I_h}{I_1}\right)^2}{\sum_{h=1}^{h=\max} \left(\frac{I_h}{I_1}\right)^2} \quad (10)$$

The harmonic loss factor for other stray losses is expressed in a similar form as for the winding eddy current. These losses are calculated based on the calculation in Table 4 for the considered harmonic spectrum of Table 5 [40].

3. Calculation and Analysis of Losses, 25 KVA Transformers Feed with PV Inverter

The rating of single-phase distribution transformer used in Rajasthan power distribution are summarized in Table 2 [41].

Table 2 Calculation and Analysis of Losses

V_1(V)	V_2(V)	I_1(A)	I_2(A)	P_o(W)	P_{sc}(W)
6358	240	3.94	104	22	281.72

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The total stray loss, P_{TSL}, can be calculated as follows:

$$Ptsl = Psc - P_{dc} = P_{ec} + Posl \quad (11)$$

$$Ptsl = Psc - P_{dc} = 281.72 - 238.90 = 42.82w$$

The winding eddy current loss and other stray losses are calculated from total stray losses. According to IEEE. Std C57.110[42-44], assumption is made that approx 67% of the total stray loss is assumed to be other stray losses for liquid-filled transformers.

$Poslr = .67*P_{tsl} = 28.69w$

$Pecr = .33*P_{tsl} = 14.13w$

Table 3 Losses with Consideration of Odd and Even Harmonics

Losses types	At full load loss(w)	Losses with RMS (h).current(w)	Harmonic loss factor	Corrected loss full load (w)
No-load	22	--	---	22
dc	238.90	238.9*1.006=240.33		240.33
Winding eddy current	14.13	14.13*1.16=16.39	1.81	29.66
Other stray Loss	28.69	28.69*1.03=29.55	1.03	30.14
Total	303.72	--	--	322.13

Table 4 Calculated Value in Tabulated Form [45]

h^2	$(I_h/I_1)^2$	$(I_h/I_1)^2 * h^2$	$h^{.8}$	$(I_h/I_1)^2 * h^{.8}$
1	1	1	1	1
4	0.0001263	0.0005052	1.74110	0.0002
9	0.0010595	0.0095355	2.40822	0.0025
16	6.812E-06	0.000108992	3.03143	2.07E-05
25	0.0012013	0.0300325	3.62389	0.00435
36	1.538E-06	0.000055368	4.19296	6.45E-06
49	0.000125	0.006125	4.74327	0.00059
64	0.0000064	0.00041088	5.27803	3.39E-05
81	0.0023426	0.1897506	5.79954	0.01358
100	0.0000722	0.00722	6.30957	0.00045
121	0.0000476	0.0057596	6.80948	0.00032
144	0.0000628	0.00905472	7.30037	0.00045
169	0.0000261	0.0044109	7.78313	0.00020
196	0.0001117	0.0218932	8.25852	0.00092
225	0.0000098	0.00220725	8.72716	8.56E-05
256	0.000025	0.0064	9.18958	0.00023
289	0.0002173	0.0627997	9.64626	0.00209
324	0.0000341	0.01105164	10.0976	0.00034
361	0.0001281	0.0462441	10.5439	0.00135
400	0.0000502	0.020108	10.9856	0.00055
441	0.0000246	0.0108486	11.4228	0.00028
484	0.0000156	0.00758912	11.856	0.00018
529	0.0000432	0.02288454	12.2852	0.0005
576	0.0000123	0.00713664	12.71069	0.0001
625	0.0001764	0.11025	13.1326	0.0023
676	3.686E-06	0.00249176	13.5512	4.99E-5
729	0.0000369	0.02695113	13.9666	0.0005
784	0.0001426	0.1117984	14.3789	0.0020
841	7.9745E-05	0.06706555	14.7883	0.0011
900	4.5024E-05	0.0405216	15.1948	0.0006
Σ	1.0062349	1.8121046		1.036

Table 5 Losses Without Consideration of Even Harmonics

Losses Types	Rated Loss (W)	Losses Rms H.Current(W)	Harmonic Loss Factor	Corrected Loss (W)
No-load	22	22	------	22
DC	238.90	238.9*1.06=260.401		253.23
Winding Eddy Current	14.13	14.13*1.2=17.60	1.24	21.91
Other Stray Loss	28.69	28.69*1.005=28.85	1.03	29.69
Total	303.72			323.84

Conclusion

The result was generated with and without consideration of even current harmonics of the PV inverter using Mat lab programming [46]. it is observed that single phase 25 kVA oil Transformer overall losses rise 6.06 % in case of consideration of even & odd current harmonics spectrum of inverter and 6.62% without consideration of even current harmonics of PV inverter [47]. The harmonic losses factor for eddy current winding and other stray losses has been computed. The value of FHL-EC= 1.81 and FHL-STR=1.02 in the case of all harmonics under consideration. The harmonic losses factor for eddy current winding and other stray losses has again been computed. The value of FHL= 1.24 and FHL-STR=1.03 in case of odd harmonics under consideration [48].

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