An Analysis into the Effect of Voltage Harmonics on the Maximum Loading Capability of Transformers

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***Abstract*—In this paper, some exemplary cases are presented to show the effect of voltage total harmonic distortion (*THDV*) and its spectrum on the harmonic loss factors (F_{HL} and F_{HL-STR}) of the six-pulse rectifiers accompanied with a constant power dc load and a battery. Accordingly, the winding losses and maximum loading capability of a transformer supplying both non-linear load types are investigated for sinusoidal and non-sinusoidal bus voltage conditions. The obtained numerical results clearly shows that the current harmonics of the considered non-linear load types are highly dependent on the *THDV* level and spectrum of the supply voltage, thus, the voltage harmonic profile should be considered in the design stage of the transformers, which are under influence of particular to supply them.**

***Index Terms*—Transformers, winding losses, harmonics, maximum loading capability.**

I. INTRODUCTION

Power systems are planned to operate under sinusoidal load currents with supply voltage-frequency. However, nonlinear loads cause non-sinusoidal or harmonically distorted currents and voltages in the systems [1]. Harmonics have a number of adverse effects on power system components and loads. One of the most important adverse effects is overheating of the transformers [2]. The overheating problem is mainly caused by the current harmonics since the additional winding loss related with current harmonics is considerably larger than the additional core loss related with voltage harmonics [3], [4]. Thus, an efficient technique, called as derating, is employed to prevent overheating of the transformers under non-sinusoidal current conditions in several studies [5]-[8]. Derating can be interpreted as the intentional reduction in loading capability of a transformer supplying a non-linear load [6], [8]. In these studies, two indices named as (i) the harmonic loss factor (F_{HL}) defined in IEEE standard C57.110 [9] and (ii) *K* factor [6] defined in UL standard 1561 [10] are generally employed for the determination of the derating factor (maximum permissible loading capability ratio) of a transformer supplying a non-linear load. On the other hand, it is well known from the literature that supply voltage harmonics may affect the current harmonic distortion of the non-linear loads [11]-[13]. This case means that voltage harmonic profile may indirectly affect the winding loss or maximum permissible loading capability of a transformer under non-sinusoidal conditions.

In this paper, F_{HL} and F_{HL-STR} values of two kinds of the six-pulse rectifiers accompanied with a constant power dc load and a battery are investigated under sinusoidal and non-sinusoidal voltage cases. Therefore, it is aimed to analyze the indirect effect of voltage harmonics on the winding loss and the maximum permissible loading capability of the transformers, which are dedicated to supply both kinds of non-linear loads.

II. IEEE STANDARD C57.110 DERATING METHOD

Winding or load loss (P_{LL}) of the transformers can be divided into three kinds of losses such as dc or Ohmic loss (P_{DC}), eddy-current loss (P_{EC}) in windings and other stray loss (P_{OSL}):

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \tag{1}$$

P_{OSL} is sum of the losses in structural parts of transformer such as tank, clamps, and P_{DC} can be expressed in terms of winding dc resistance (R_{DC}) and square of the total rms value of the load individual harmonic currents (I_h);

$$P_{DC} = R_{DC} I^2 = R_{DC} \sum_h I_h^2 \tag{2}$$

Note that according to IEEE standard C57.110, P_{EC} is 67% and 33% of the total stray losses ($P_{TSL} = P_{LL} - P_{DC}$) for dry-type and liquid-filled transformers, respectively.

For linear rated load case, eq. (1) can be written as;

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \tag{3}$$

where P_{LL-R} is rated load loss, P_{EC-R} is rated winding eddy-current loss, and P_{OSL-R} is rated other stray loss at rated current. In IEEE standard C57.110, for the maximum permissible loading capability of the transformers under balanced non-sinusoidal current conditions, F_{HL} and F_{HL-STR} indices were defined:

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$$F_{HL} = \sum_h h^2 \left(\frac{I_h}{I_1}\right)^2 \Bigg/ \sum_h \left(\frac{I_h}{I_1}\right)^2 \qquad (4)$$

$$F_{HL-STR} = \sum_h h^{0.8} \left(\frac{I_h}{I_1}\right)^2 \Bigg/ \sum_h \left(\frac{I_h}{I_1}\right)^2 \qquad (5)$$

By using F_{HL} and $F_{HL\text{-}STR}$ indices, the same standard expressed P_{LL} as follows;

$$P_{LL}(pu) = I^2(pu)\left[1 + F_{HL} P_{EC-R}(pu) + F_{HL-STR} P_{OSL-R}(pu)\right] \qquad (6)$$

Thus, the ratio of the transformer's maximum permissible current to the rated current (I_R) or the transformer maximum loading capability was derived from eq. (6):

$$\frac{I_{\max}}{I_R} = \sqrt{\frac{P_{LL-R}(pu)}{1 + F_{HL} P_{EC-R}(pu) + F_{HL-STR} P_{OSL-R}(pu)}} \qquad (7)$$

Note that since the temperature rise in the non-winding parts generally is not very critical for dry-type transformers [9], for that kind of transformers, eq. (6) and (7) can be rearranged as follows;

$$P_{LL}(pu) = I^2(pu)\left[1 + F_{HL} P_{EC-R}(pu)\right] \qquad (8)$$

$$\frac{I_{\max}}{I_R} = \sqrt{\frac{P_{LL-R}(pu)}{1 + F_{HL} P_{EC-R}(pu)}} \qquad (9)$$

III. Analysis Results

This study aims to analyze effect of voltage harmonics on F_{HL}, $F_{HL\text{-}STR}$ and I_{max}/I_R values of the transformers supplying the six-pulse rectifier based non-linear loads. For this goal, several voltage harmonic distortion and two load scenarios are simulated in the test system (see Figure 1). The test system consists of a variable voltage source, which is employed to result in any non-sinusoidal test voltage at the bus, a liquid-filled distribution transformer, of which ratings 12.5 MVA and 31.5 kV (star)/11 kV (delta), two different six-pulse rectifiers accompanied with (i) a constant power dc load (P=10 MVA, C=600µF) and (ii) a battery (V_{dc}= 10600V, R_{dc}=5Ω, C=600µF). Note that pu values of the rated P_{EC} and P_{OSL} of the transformer are 0.055 and 0.110, respectively.

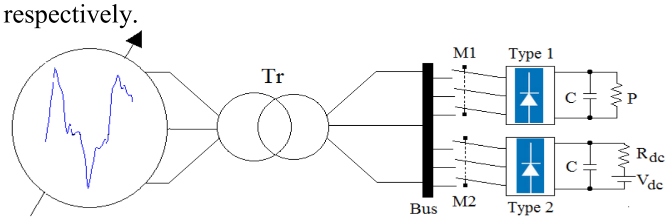

Figure 1: The simulated system.

By means of the system, both types of six-pulse rectifiers are supplied under four different bus voltage cases. First one (Case 1) of these supply cases is sinusoidal voltage condition. On the other hand, for three non-sinusoidal bus voltage cases (Case 2-4) with 10% of *THDV* level. The non-sinusoidal voltages considered in Case 2-4 have different harmonic spectrums to figure out the effect of voltage harmonic spectrum on the transformer derating (see Table I). For all four cases, the phase-to-neutral bus voltages are balanced, and phasor values of their fundamental frequency components are kept as $6350\angle 0^\circ$ V, $6350\angle 240^\circ$ V and $6350\angle 120^\circ$ V.

Table I: Phasor values of the phase-to-neutral bus voltage harmonics (h>1) for Case 2-4.

Case No	$\bar{V}_{ah}$ (V)	$\bar{V}_{bh}$ (V)	$\bar{V}_{ch}$ (V)
2	$\frac{2234}{h}\angle 0^\circ$	$\frac{2234}{h}\angle h\cdot 240^\circ$	$\frac{2234}{h}\angle h\cdot 120^\circ$
	h= only odd harmonic orders up to 20th harmonic (except triplen harmonics)		
3	$\frac{968}{h}\angle 0^\circ$	$\frac{968}{h}\angle h\cdot 240^\circ$	$\frac{968}{h}\angle h\cdot 120^\circ$
	h= both even and odd harmonic orders up to 20th harmonic (except triplen harmonics)		
4	$\frac{968}{h}\angle -180^\circ$	$\frac{968}{h}\angle h\cdot 240^\circ - 180^\circ$	$\frac{968}{h}\angle h\cdot 120^\circ - 180^\circ$
	h= both even and odd harmonic orders up to 20th harmonic (except triplen harmonics)		

For the six-pulse rectifier with a constant power dc load (Type 1 load) and the six-pulse rectifier with a battery (Type 2 load), the harmonic loss factor or the maximum permissible loading capability of the transformer are found under the above mentioned four different bus voltage cases (Case 1-4) with using Simulink/MATLAB software [14]. The results are detailed below.

A. *Transformer derating results for Type 1 load under Case 1-4 bus voltage conditions*

For four bus voltage cases from Case 1 to Case 4, the harmonic current spectrums, F_{HL} and $F_{HL\text{-}STR}$ terms of the Type 1 load are given in Table II, III, IV and V, respectively.

One can observe from these tables that under the sinusoidal bus voltage and the non-sinusoidal bus voltage cases with only odd harmonics (Case 1 and 2), phase currents of Type 1 load have its typical current harmonic orders (h=1, 5, 7, 11, 13, 17, 19). However, for the non-sinusoidal bus voltage cases with all (even and odd) harmonic orders (Case 3 and 4), phase currents of the same load have both typical and non-typical harmonic orders. In addition, it is also seen from these tables that current harmonics of the load are sensitive to both voltage total harmonic distortion (*THDV*) and voltage harmonic spectrum. For Case 1-4 of the three-phase bus voltages, the F_{HL} values of the Type 1 load are calculated as 25.60, 40.85, 23.20 and 32.73, respectively. On the other hand, for Case 1-4, the $F_{HL\text{-}STR}$ values are found as 2.54, 2.70, 2.30 and 2.75, respectively. Additionally, Table VI shows that eddy current loss (P_{EC}) has the pu values as 1.41, 2.23, 1.25 and 1.80 for Case 1-4. It is also pointed out from the same table that other stray loss (P_{OSL}) are calculated as 0.28, 0.30, 0.25 and 0.29 for Case 1-4.

Thus, it can be concluded for the transformer supplying Type 1 load that F_{HL} and P_{EC} are highly dependent on *THDV* level and voltage harmonic spectrum. But, this is not the case for F_{HL-STR} and P_{OSL}. As a result, considerably different I_{max}/I_R values such as 66%, 57%, 68% and 61% are observed for Case 1-4 of the bus voltages, and the maximum difference among the calculated I_{max}/I_R values is 11%.

Table II: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 1 load for Case 1 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	1.0000	1.0000	1.0000	1.0000
2	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
3	0.0001	$2.27x10^{-8}$	$2.04x10^{-7}$	$5.46x10^{-8}$
4	0.0001	$2.27x10^{-8}$	$3.63x10^{-7}$	$6,88x10^{-8}$
5	0.6566	0.4311	10.7789	1.5624
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.4231	0.1790	8.7755	0.8494
8	0.0001	$2.27x10^{-8}$	$1.45x10^{-6}$	$1.2x10^{-7}$
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.0001	$2.27x10^{-8}$	$2.27x10^{-6}$	$1.43x10^{-7}$
11	0.2093	0.0438	5.3024	0.2984
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.2078	0.0431	7.2997	0.3361
14	0.0001	$2.27x10^{-8}$	$4.45x10^{-6}$	$1.87x10^{-7}$
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.0001	$2.27x10^{-8}$	$5.81x10^{-6}$	$2.08x10^{-7}$
17	0.1400	0.0196	5.6692	0.1892
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.1234	0.0152	5.5055	0.1608
20	0.0001	$2.27x10^{-8}$	$9.07x10^{-6}$	$2.49x10^{-7}$
F_{HL}		25.60		
F_{HL-STR}		2.54		

Table III: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 1 load for Case 2 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	0.9728	0.9465	0.9465	0.9465
2	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
3	0.0001	$2.27x10^{-8}$	$2.04x10^{-7}$	$5.46x10^{-8}$
4	0.0001	$2.27x10^{-8}$	$3.63x10^{-7}$	$6.88x10^{-8}$
5	0.5135	0.2637	6.5934	0.9557
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.2771	0.0767	3.7626	0.3642
8	0.0001	$2.27x10^{-8}$	$1.45x10^{-6}$	$1.2x10^{-7}$
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.0001	$2.27x10^{-8}$	$2.27x10^{-6}$	$1.43x10^{-7}$
11	0.2334	0.0544	6.5934	0.3710
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.1686	0.0284	4.8082	0.2214
14	0.0001	$2.27x10^{-8}$	$4.45x10^{-6}$	$1.87x10^{-7}$
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.0001	$2.27x10^{-8}$	$5.81x10^{-6}$	$2.08x10^{-7}$
17	0.2153	0.0463	13.4039	0.4473
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.2605	0.0678	24.5054	0.7157
20	0.0001	$2.27x10^{-8}$	$9.07x10^{-6}$	$2.49x10^{-7}$
F_{HL}		40.85		
F_{HL-STR}		2.70		

Table IV: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 1 load for Case 3 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	0.9894	0.9790	0.9790	0.9790
2	0.3418	0.1168	0.4674	0.2034
3	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
4	0.2846	0.0810	1.2963	0.2456
5	0.4879	0.2380	5.9524	0.8628
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.2078	0.0431	2.1164	0.2048
8	0.2695	0.0726	4.6510	0.3835
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.2213	0.0490	4.9011	0.3092
11	0.0331	0.0010	0.1328	0.0074
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.0286	0.0008	0.1383	0.0063
14	0.1385	0.0191	3.7626	0.1585
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.1415	0.0200	5.1304	0.1841
17	0.0617	0.0038	1.1018	0.0367
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.0376	0.0014	0.5117	0.0149
20	0.1325	0.0175	7.0256	0.1929
F_{HL}		23.20		
F_{HL-STR}		2.30		

Table V: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 1 load for Case 4 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	1.0136	1.0273	1.0273	1.0273
2	0.3193	0.1019	0.4078	0.1775
3	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
4	0.2952	0.0871	1.3941	0.2641
5	0.6220	0.3869	9.6717	1.4020
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.3584	0.1285	6.2953	0.6094
8	0.2666	0.0711	4.5477	0.3750
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.2425	0.0588	5.8792	0.3710
11	0.0753	0.0057	0.6861	0.0386
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.0572	0.0033	0.5535	0.0255
14	0.2139	0.0457	8.9639	0.3777
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.2184	0.0477	12.2079	0.4382
17	0.0633	0.0040	1.1563	0.0386
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.1160	0.0134	4.8546	0.1418
20	0.1401	0.0196	7.8467	0.2155
F_{HL}		32.73		
F_{HL-STR}		2.75		

Table VI: I_{max}/I_R, P_{EC} and P_{OSL} values for the transformer supplying Type 1 load under the Case 1-4 of the bus voltages.

Cases	$P_{EC}=F_{HL}P_{EC-R}$	$P_{OSL}=F_{HL-STR}P_{OSL-R}$	I_{max}/I_R
1	1.41 pu	0.28 pu	66%
2	2.23 pu	0.30 pu	57%
3	1.25 pu	0.25 pu	68%
4	1.80 pu	0.29 pu	61%

B. Transformer derating results for Type 2 load under Case 1-4 bus voltage conditions

Under four cases of the bus voltages from Case 1 to Case 4, the harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 2 load are presented in Table VII, VIII, IX and X, respectively.

Table VII: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 2 load for Case 1 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	1.0000	1.0000	1.0000	1.0000
2	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
3	0.0001	$2.27x10^{-8}$	$2.04x10^{-7}$	$5.46x10^{-8}$
4	0.0001	$2.27x10^{-8}$	$3.63x10^{-7}$	$6,88x10^{-8}$
5	0.6434	0.4140	10.3516	1.5005
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.3985	0.1588	7.7832	0.7534
8	0.0001	$2.27x10^{-8}$	$1.45x10^{-6}$	$1.2x10^{-7}$
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.0001	$2.27x10^{-8}$	$2.27x10^{-6}$	$1.43x10^{-7}$
11	0.1840	0.0338	4.0991	0.2306
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.1927	0.0371	6.2790	0.2891
14	0.0001	$2.27x10^{-8}$	$4.45x10^{-6}$	$1.87x10^{-7}$
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.0001	$2.27x10^{-8}$	$5.81x10^{-6}$	$2.08x10^{-7}$
17	0.1246	0.0155	4.4894	0.1498
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.1101	0.0121	4.3796	0.1279
20	0.0001	$2.27x10^{-8}$	$9.07x10^{-6}$	$2.49x10^{-7}$
F_{HL}		23.96		
F_{HL-STR}		2.42		

Table VIII: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 2 load for Case 2 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	0.9246	0.8549	0.8549	0.8549
2	0.0001	$2.27x10^{-8}$	$9.07x10^{-8}$	$3.95x10^{-8}$
3	0.0001	$2.27x10^{-8}$	$2.04x10^{-7}$	$5.46x10^{-8}$
4	0.0001	$2.27x10^{-8}$	$3.63x10^{-7}$	$6.88x10^{-8}$
5	0.4942	0.2442	6.1059	0.8850
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.2565	0.0658	3.2243	0.3121
8	0.0001	$2.27x10^{-8}$	$1.45x10^{-6}$	$1.2x10^{-7}$
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.0001	$2.27x10^{-8}$	$2.27x10^{-6}$	$1.43x10^{-7}$
11	0.2072	0.0429	5.1970	0.2924
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.1565	0.0244	4.1403	0.1906
14	0.0001	$2.27x10^{-8}$	$4.45x10^{-6}$	$1.87x10^{-7}$
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.0001	$2.27x10^{-8}$	$5.81x10^{-6}$	$2.08x10^{-7}$
17	0.1927	0.0371	10.7374	0.3583
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.2463	0.0607	21.9132	0.6400
20	0.0001	$2.27x10^{-8}$	$9.07x10^{-6}$	$2.49x10^{-7}$
F_{HL}		39.21		
F_{HL-STR}		2.65		

Table VII-X show that for Case 1 and 2 of the bus voltages, phase currents of Type 2 load have its typical current harmonic orders, and for Case 3 and 4 of the bus voltages, it draws both typical and non-typical current harmonic orders. Similar to Type 1 load, it should be mentioned that current harmonics of the Type 2 load are sensitive to *THDV* level and harmonic spectrum of the bus voltage.

For Case 1-4 of the three-phase bus voltages, the F_{HL} values of the Type 2 load are calculated as 23.96, 39.21, 21.00 and 29.00, respectively. Under the same bus voltage cases, the observed F_{HL-STR} values are 2.42, 2.65, 2.22 and 2.60. According to the determined F_{HL} and F_{HL-STR} values (given in Table VII-X), P_{EC} and P_{OSL} are found as in Table XI. This table figure out that P_{EC} has the pu values as 1.30, 2.18, 1.14 and 1.58 for Case 1-4. Pu values of P_{OSL} are 0.26, 0.29, 0.24 and 0.28 for the respective cases. Thus, I_{max}/I_R values of the transformer, which supplies Type 2 load under Case 1-4 bus voltages, are determined as 67%, 57%, 69% and 63%, respectively. Here, it should be underlined that the maximum difference among the determined I_{max}/I_R values is about 12%. Above detailed results clearly interpret that voltage harmonic profile should be taken into account for the determination of the maximum loading capability (I_{max}/I_R) of a transformer supplying Type 1 or Type 2 load.

Table IX: Harmonic current spectrums, F_{HL} and F_{HL-STR} terms of the Type 2 load for Case 3 of the bus voltages.

h	$I_h(pu)$	$[I_h(pu)]^2$	$h^2[I_h(pu)]^2$	$h^{0.8}[I_h(pu)]^2$
1	0.9811	0.9626	0.9626	0.9626
2	0.3710	0.1376	0.5506	0.2396
3	0.0001	$2.27x10^{-8}$	$2.04x10^{-7}$	$5.46x10^{-8}$
4	0.2579	0.0665	1.0647	0.2017
5	0.4855	0.2357	5.8929	0.8542
6	0.0001	$2.27x10^{-8}$	$8.17x10^{-7}$	$9.51x10^{-8}$
7	0.2028	0.0411	2.0172	0.1952
8	0.2420	0.0585	3.7489	0.3091
9	0.0001	$2.27x10^{-8}$	$1.84x10^{-6}$	$1.32x10^{-7}$
10	0.2101	0.0441	4.4160	0.2786
11	0.0376	0.0014	0.1718	0.0096
12	0.0001	$2.27x10^{-8}$	$3.27x10^{-6}$	$1.66x10^{-7}$
13	0.0159	0.0002	0.0429	0.0019
14	0.1173	0.0137	2.7010	0.1138
15	0.0001	$2.27x10^{-8}$	$5.1x10^{-6}$	$1.98x10^{-7}$
16	0.1347	0.0181	4.6505	0.1669
17	0.0536	0.0028	0.8310	0.0277
18	0.0001	$2.27x10^{-8}$	$7.35x10^{-6}$	$2.29x10^{-7}$
19	0.0217	0.0004	0.1706	0.0049
20	0.1333	0.0177	7.1111	0.1952
F_{HL}		21.00		
F_{HL-STR}		2.22		

Table X: Harmonic current spectrums, F_{HL} and $F_{HL\text{-}STR}$ terms of the Type 2 load for Case 4 of the bus voltages.

h	$I_h(pu)$	$\left[I_h(pu)\right]^2$	$h^2\left[I_h(pu)\right]^2$	$h^{0.8}\left[I_h(pu)\right]^2$
1	1.0478	1.0979	1.0979	1.0979
2	0.3449	0.1189	0.4759	0.2071
3	0.0001	$2.27\text{x}10^{-8}$	$9.07\text{x}10^{-8}$	$3.95\text{x}10^{-8}$
4	0.2739	0.0750	1.2004	0.2274
5	0.6289	0.3956	9.8905	1.4336
6	0.0001	$2.27\text{x}10^{-8}$	$8.17\text{x}10^{-7}$	$9.51\text{x}10^{-8}$
7	0.3492	0.1219	5.9776	0.5786
8	0.2304	0.0531	3.3984	0.2802
9	0.0001	$2.27\text{x}10^{-8}$	$1.84\text{x}10^{-6}$	$1.32\text{x}10^{-7}$
10	0.2260	0.0511	5.1115	0.3225
11	0.0797	0.0063	0.7687	0.0432
12	0.0001	$2.27\text{x}10^{-8}$	$3.27\text{x}10^{-6}$	$1.66\text{x}10^{-7}$
13	0.0681	0.0046	0.7841	0.0361
14	0.1884	0.0354	6.9573	0.2931
15	0.0001	$2.27\text{x}10^{-8}$	$5.1\text{x}10^{-6}$	$1.98\text{x}10^{-7}$
16	0.2014	0.0405	10.3889	0.3729
17	0.0521	0.0027	0.7866	0.0262
18	0.0001	$2.27\text{x}10^{-8}$	$7.35\text{x}10^{-6}$	$2.29\text{x}10^{-7}$
19	0.0985	0.0097	3.5061	0.1024
20	0.1463	0.0214	8.5704	0.2353
F_{HL}		29.00		
$F_{HL\text{-}STR}$		2.60		

Table XI: $I_{\max}/I_R$, P_{EC} and P_{OSL} values for the transformer supplying Type 2 load under the Case 1-4 of the bus voltages.

Cases	$P_{EC}=F_{HL}P_{EC-R}$ (pu)	$P_{OSL}=F_{HL-STR}P_{OSL-R}$ (pu)	$I_{\max}/I_R$
1	1.30	0.26	67%
2	2.18	0.29	57%
3	1.14	0.24	69%
4	1.58	0.28	63%

IV. CONCLUSION

In this study, the harmonic loss factors (F_{HL} and $F_{HL\text{-}STR}$) of the six-pulse rectifiers, which are accompanied with a constant power dc load and a battery, are evaluated for sinusoidal voltage case (Case 1) and three-different non-sinusoidal voltage cases (Case 2-4). The non-sinusoidal voltage cases have the same *THDV* level as 10% but consist of different harmonic spectrums. Accordingly, by means of the simulation results, the winding loss and maximum loading capability of the transformer supplying both nonlinear load types are analyzed for the considered supply voltage conditions.

It is concluded from the analysis results that the difference among the transformer maximum loading capability values, which are determined under the considered supply voltage cases, can be larger than 10%. This case means that the utility voltage's harmonic profile should be taken into account for the design of the transformers, which are dedicated to supply the considered six-pulse rectifier-based load types.

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