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Optimal Design of Single-Tuned Passive Filters to Minimize Harmonic Loss Factor

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Abstract: Transformers are conventionally designed for operation under sinusoidal load currents with supply voltage-frequency. The non-sinusoidal or harmonically distorted currents drawn by non-linear loads lead to excessive winding losses and overheating of the transformers. These adverse effects result in loss of useful life of the transformers. To prevent the excessive winding losses, the transformers should be loaded at less than their rated loading capacity under non-sinusoidal load current conditions. In IEEE standard C57.110, the loading capacity of the transformer, which is dedicated to supply a non-linear load, is determined in terms of the harmonic loss factor (F_{HL}). The same standard also figured out that the loading capacity of a transformer is inversely proportional to the F_{HL} index of the supplied non-sinusoidal current. The main purpose of this paper is to employ the passive filters for maximization of the loading capacity of the transformers under non-linear load conditions. Thus, an optimal passive filter design approach is proposed regarding minimization of F_{HL}. With respect to IEEE standard 519, voltage total harmonic distortion (THDV), current total harmonic distortion (THDI) and displacement power factor (DPF) are considered as three constraints for the proposed approach. Numerical results are presented to show that the proposed approach provides higher loading capacity of the transformers when compared with the traditional filter design approach based on minimization of THDI.

Key words: Harmonics · Non-linear loads · Transformer loading capacity · Passive filters

INTRODUCTION

Transformers are conventionally designed for operation under sinusoidal load currents with supply voltage-frequency. However, the non-linear loads, which have harmonically distorted or non-sinusoidal current wave shapes, are largely proliferated in the modern industrial power systems [1, 2]. Thus, in the literature, great interests have been focused on the effects of the harmonics on the transformers [3-23]. It is seen from these studies that non-sinusoidal currents cause excessive winding losses, which result in overheating and useful life reduction of the transformers. These studies also employ an effective technique, widely called as derating [9, 13-15, 17-19], to prevent the excessive winding losses related with the current harmonics. Derating is the intentional reduction in loading capacity of a transformer, which is dedicated to supply a non-linear load. In addition to that, derating ratio (permissible loading capacity) of a transformer under non-linear load conditions is determined in Underwriters Laboratories (UL) standard 1561 [24] and IEEE standard C57.110 [25, 26]. In UL std. 1561, derating ratio is expressed in terms of K-factor for dry-type transformers. The determination of the derating ratio, which is recommended by IEEE std. C57.110, is based on F_{HL} index. IEEE standard method covers both dry-type and liquid filled transformers. In addition, two standards clearly concluded that the transformer's loading capacity is inversely proportional to K-factor and F_{HL} indices.

In parallel with these standards, transformer production companies started to design the transformers, which are dedicated to supply the non-linear loads such as adjustable speed drives, power rectifiers and inverters, etc., by considering the rated powers and F_{HL} or K-factor values of the loads [27-29].

On the other hand, it is reported in [30] that the studies focused on the optimal filter design aim to achieve many combinations of five goals such as (I) minimization of current total harmonic distortion (THDI), (ii)

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minimization of voltage total harmonic distortion (THDV), (iii) maximization of power factor, (iv) minimization of the filter's loss, (v) minimization of the filter's investment cost. Therefore, it can be concluded that the passive harmonic filters are not employed as equipment for maximization of the transformer's loading capacity under non-sinusoidal current conditions in the literature.

Consequently, in this paper, the passive harmonic filters are designed for minimization of F_{HL} index or maximization of transformer loading capacity under non-sinusoidal current conditions. Displacement power factor (DPF), THDI and THDV limits recommended by IEEE std. 519 [31] are considered as three constraints in the optimal filter design process. For the typical industrial power system, which is used as an exemplary system in several optimal filter design studies [30, 32-35], the proposed approach is comparatively evaluated with respect to the traditional optimal filter design approach based on the minimization of THDI (I).The numerical results show that the proposed approach provides higher loading capacity of the transformer under a non-sinusoidal load current condition when compared with the traditional one. This is an important finding for effective utilization of transformers in the non-sinusoidal power systems.

Modeling of the Typical Industrial Power System: The one line diagram of the typical industrial power system is shown in Figure 1, which consists of a consumer with three-phase linear and non-linear loads, a single-tuned LC filter connected to load bus and the consumer's transformer.

In order to state the current, voltage and power expressions for the system, its single-phase equivalent circuit (given in Figure 2) can practically be used. This practical solution is valid due to the fact that the system is balanced. In the figure, a linear impedance ($R_L + jhX_L$) and a constant current source per harmonic ($\underline{I}_{Lh}$) denote the linear and non-linear load model parameters [36], which are referred to the primary side of the transformer. On the other hand, utility side is modelled as Thevenin equivalent voltage source ($\underline{V}_{Sh}$) and Thevenin equivalent impedance ($\underline{Z}_{Sh}$) for each harmonic number.

The consumer's transformer is modelled using its short circuit impedance, which is referred to its primary side:

$$\underline{Z}_{Trh} = R_{dc} + h^2 R_{ec} + jhX_{Tr} \tag{1}$$

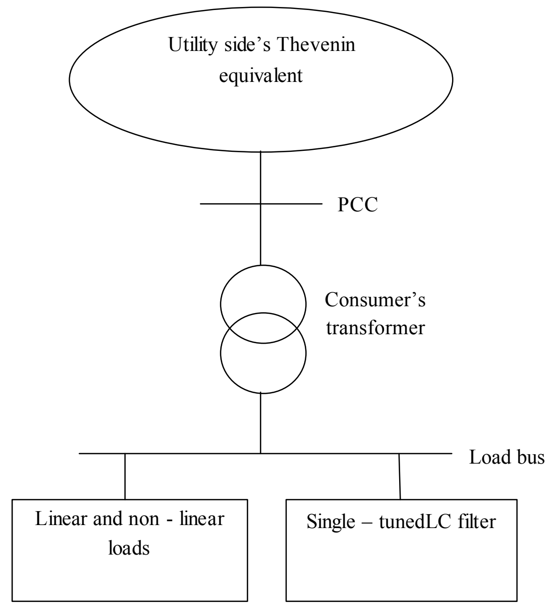

Fig. 1: One line diagram of the typical industrial power system.

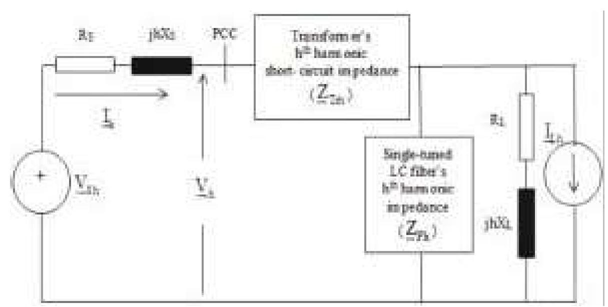

Fig. 2: Single-phase equivalent circuit of the typical industrial power system.

where X_{tr} is the winding's fundamental harmonic inductive reactance, R_{dc} and R_{ec} denote the winding's dc resistance and the winding's equivalent resistance corresponding to the eddy-current loss, respectively.

Using the superposition principle, the current and voltage expressions can be written for the single-phase equivalent circuit as follows:

$$\underline{I}_h = \frac{\underline{V}_{Sh}}{\underline{Z}_{Sh} + \underline{Z}_{Trh} + \underline{Z}_{FLh}} + \frac{\underline{Z}_{FLh}}{\underline{Z}_{Sh} + \underline{Z}_{Trh} + \underline{Z}_{FLh}} \underline{I}_{Lh} \tag{2}$$

$$\underline{V}_h = \underline{V}_{Sh} - \underline{I}_h \underline{Z}_{Sh} \tag{3}$$

where $\underline{Z}_{FLh}$ is the parallel equivalent of the load's h^{th} harmonic impedance ($R_L + jhX_L$) and h^{th} harmonic impedance of the single-tuned passive filter

($\underline{Z}_{Fh} = j\left(hX_{LF} - \frac{X_{CF}}{h}\right)$), which are referred to the primary side of the transformer. Note that $\underline{Z}_{FLh}$ can be expressed as;

$$\underline{Z}_{FLh} = \frac{\underline{Z}_{Fh}\left(R_L + jhX_L\right)}{\left(\underline{Z}_{Fh} + R_L + jhX_L\right)} = \frac{j\left(hX_{LF} - \frac{X_{CF}}{h}\right)\left(R_L + jhX_L\right)}{\left[j\left(hX_{LF} - \frac{X_{CF}}{h}\right) + R_L + jhX_L\right]} \quad (4)$$

The subscript (_) denotes phasor values of the respective voltage, current and impedances. Considering the voltage and current harmonics, which are found from and, THDV and THDI can be calculated as follows:

$$THDV = \frac{\sqrt{\sum_{h\neq 1} V_h^2}}{V_1} \quad (5)$$

$$THDI = \frac{\sqrt{\sum_{h\neq 1} I_h^2}}{I_1} \quad (6)$$

In addition, one can express fundamental harmonic active powers (P_1) and fundamental harmonic apparent powers (S_1)at each-phase of the PCC as below:

$$P_1 = V_1 I_1 \cos\varphi_1 \quad (7)$$

$$S_1 = V_1 I_1 \quad (8)$$

Thus, the displacement power factor (DPF) can be found in terms of P_1 and S_1:

$$DPF = \frac{P_1}{S_1} = \cos\varphi_1 \quad (9)$$

Finally, for the system, the F_{HL} index, which is placed in IEEE std.C57.110, can be calculated as follows:

$$F_{HL} = \sum_h h^2 \left(\frac{I_h}{I_1}\right)^2 \Big/ \sum_h \left(\frac{I_h}{I_1}\right)^2 \quad (10)$$

By means of the calculated F_{HL} value, the permissible current capacity ($I_{\max}(pu)$) and permissible loading capacity ($S_{\max}(\%)$) of the transformer can be determined:

$$I_{\max}(pu) = \sqrt{\frac{P_{LL-R}(pu)}{1 + F_{HL}P_{EC-R}(pu)}} = \sqrt{\frac{1 + P_{EC-R}(pu)}{1 + F_{HL}P_{EC-R}(pu)}} \quad (11)$$

$$S_{\max}(\%) = \sqrt{3}V_R(pu)I_{\max}(pu)\cdot 100 \quad (12)$$

where V_R(pu), P_{LL-R}(pu) and P_{EC-R}(pu) are pu values of the rated line - to-line voltage, winding rated loss and winding eddy-current rated loss of the transformer, respectively. One can see from -that F_{HL}, I_{max}(pu) and S_{max} are 1, 1 pu and 100% under rated sinusoidal current condition. In addition, $F_{HL}>1$, I_{max}(pu)<1pu and S_{max}<100% will be observed if the current has a non-sinusoidal wave shape.

The proposed and traditional optimal passive filter design approaches will be formulated and solved regarding the detailed model of the typical industrial power system in the next sections.

Formulation of Optimal Filter Design Problem: As mentioned above, the passive harmonic filters can be employed for maximization of the transformer's loading capacity under non-sinusoidal load current conditions. To achieve this goal, minimization of F_{HL} indexes used as an objective function for the optimal passive filter design problem. THDI and THDV indices are considered as two constraints in the optimization problem due to the fact that both indices are taken under limitation by IEEE std. 519 for several levels of the supply voltage and short circuit power of the power systems. On the other hand, the same standard recommended that a lagging DPF is necessary with a value between 95% and 100%. Thus, DPF is a third constraint of the optimization problem. After defining the objective function and constraints, optimal design problem of the single-tuned passive filter becomes:

$$Minimize\ F_{HL}\left(X_{LF}, X_{CF}\right) \quad (13)$$

Subject to

$$THDI(X_{LF}, X_{CF}) \leq THDI_{MAX} \quad (14)$$

$$THDV(X_{LF}, X_{CF}) \leq THDV_{MAX} \quad (15)$$

$$DPF(X_{LF}, X_{CF}) \leq 100\% \quad (16)$$

$$DPF(X_{LF}, X_{CF}) \geq 95\% \quad (17)$$

where eq. (13) is the objective function of the proposed optimal filter design problem and eq. (14)-(17) are the inequality constraints of the proposed optimal filter design problem. In the inequality constraints, $THDI_{MAX}$ and $THDV_{MAX}$ are the maximum allowable THDI and THDV values, which are determined in IEEE standard 519.

On the other hand, the optimal filter design studies traditionally aim to minimize THDI. These studies consider the same constraints with the proposed optimal design approach. Therefore, the traditional optimal filter design approach can be described as:

$$\textit{Minimize}\ \mathrm{THDI}\left(X_{LF}, X_{CF}\right) \tag{18}$$

Subject to

The inequality constraints presented in eq. (14)-(17).

Both optimization problems are solved by means of Grid Search Method (GSM),which is one of the oldest and the most reliable optimization techniques [37]. GSM searches all feasible X_{LF} and X_{CF} values for finding optimal solution.

It should be underlined that the traditional optimal filter design approach does not aim to maximize the loading capacity of the transformers under non-linear load conditions. Therefore, the proposed filter design approach has an advantage on the effective utilization of the transformers with respect to the traditional one.

Exemplary Cases: In this section, several exemplary cases are presented to analyze the performances of the proposed and traditional optimal filter design approaches. A typical industrial power system, which is given in Figure 1, is used for the simulations of the exemplary cases. Fundamental frequency supply voltage and short circuit power of the typical industrial power system are predetermined as 6.3 kV (line - to-line) and 210 MVA. In the typical industrial power system's single-phase equivalent circuit (illustrated in Figure 2), the impedance parameters are R_S=0.0189Ω, X_S=0.189Ω, R_L=13.67Ω, X_L=13Ω, R_{dc}=0.104Ω, R_{ec}=0.024Ω and X_{Tr}=0.882Ω. Fundamental frequency line - to-neutral source voltage (V_{S1}) and fundamental frequency line current (I_1) are 3637 V and 184 A. These values are defined as base voltage and base current values. For the first exemplary case (case 1), pu values of the voltage source and current source harmonics are presented in Table 1.

For the voltage source and current source harmonics presented in Table 1, the THDV, THDI, F_{HL}, DPF and P_1 values at the PCCbus are calculated as 2.80%, 25%, 7.05, 70.50% and 1409kW, respectively. According to the recommendations placed in IEEE std. 519, THDV and THDI levels of the simulated system do not exceed 5% and 15%, respectively. In addition, the loading capacity of the transformer (S_{max}) has a very low value, which is calculated as 69% for F_{HL}=7.05.

Table 1: Pu values of the voltage source and current source harmonics for case 1

h	$\underline{V}_{Sh}(pu)$	$\underline{I}_{Lh}(pu)$
5	0.007∠0°	0.170∠135°
7	0.004∠0°	0.143∠145°
11	0.002∠0°	0.091∠–135°
13	0.0015∠0°	0.077∠135°
17	0.0015∠0°	0.059∠–45°
19	0.001∠0°	0.53∠–135°
23	0.001∠0°	0.043∠45°
25	0.001∠0°	0.037∠–45°

Table 2: The results obtained by the proposed and traditional optimal filter design approaches for case 1.

	F_{HL} minimization (proposed approach)	THDI minimization (traditional approach)
X_{LF}	0.85 Ω	1.13 Ω
X_{CF}	27.59 Ω	27.59 Ω
THDI	13.50%	11.30%
THDV	1.11%	1.35%
DPF	99.99%	99.99%
F_{HL}	2.84	3.34
S_{max}	86.35%	84.16%

For these conditions, two different optimal filter designs are determined by considering the proposed and traditional approaches (Table 2).The values of the power quality indices (THDV, THDI, F_{HL} and DPF) and the transformer's loading capacities (S_{max}), which are achieved with both optimal filter designs, are also given in Table 2. It can clearly be seen from this table that the proposed design approach provides lower F_{HL} value (2.84) and higher S_{max} value (86.35%) when compared with the traditional design approach (F_{HL}=3.34, S_{max}=84.16%). Thus, it can be figured out that thedifference (ΔS_{max}) of the S_{max} values, which are attained by the proposed and traditional filter designs, is about 2.2%.On the other hand, the proposed one does not achieve the minimum THDI (11.30%), which is obtained by the traditionalone. Note that both approaches meet THDI and THDV limits of the IEEE std. 519. They also attain the same DPF value(99.99%).

In addition to the above mentioned results, to evaluate the performances of the proposed and traditional approaches under the highly distorted current conditions, both approaches are implemented without considering THDV and THDI constraints for case 2-6.For case 2-6, which have the current source harmonics given in Table 3, Table 4 presents the THDI, THDV and F_{HL} values at the PCC bus and the loading capacity (S_{max}) of the transformer. For these cases, the results of the proposed and traditional optimal design approaches are given in Table 5 and 6. One can see from these tables that they can provide very different F_{HL} values, particularly in the

Table 3: Pu values of the current source harmonics for case 2-6

h	$\underline{I}_{Lh}(pu)$ Case 2	Case 3	Case 4	Case 5	Case 6
5	0.204∠–135°	0.238∠–135°	0.272∠–135°	0.306∠–135°	0.340∠–135°
7	0.172∠45°	0.200∠45°	0.0229∠45°	0.257∠45°	0.286∠45°
11	0.109∠–135°	0.127∠–135°	0.146∠–135°	0.164∠–135°	0.182∠–135°
13	0.092∠135°	0.108∠135°	0.123∠135°	0.139∠135°	0.154∠135°
17	0.071∠–45°	0.083∠–45°	0.094∠–45°	0.106∠–45°	0.118∠–45°
19	0.064∠–135°	0.074∠–135°	0.085∠–135°	0.095∠–135°	0.106∠–135°
23	0.052∠–45°	0.060∠45°	0.069∠45°	0.077∠45°	0.086∠45°
25	0.044∠–45°	0.052∠–45°	0.059∠–45°	0.067∠–45°	0.078∠–45°

Table 4: For case 2-6, the THDI, THDV and F_{HL} values at the PCC bus and the loading capacity of the transformer.

	Case 2	Case 3	Case 4	Case 5	Case 6
THDV	3.25%	3.73%	4.20%	4.70%	5.17%
THDI	30%	35%	40%	45%	50%
F_{HL}	9.50	12.24	15.21	18.36	21.62
S_{max}	62.08%	56.72%	52.23%	48.47%	45.32%

Table 5: For case 2-6, the results achieved by the optimal passive filter, which is designed according to the proposed approach without considering THDI and THDV constraints.

	Case 2	Case 3	Case 4	Case 5	Case 6
X_{LF}	0.78 Ω	0.76 Ω	0.75 Ω	0.74 Ω	0.73 Ω
X_{CF}	27.59 Ω	27.59 Ω	27.59 Ω	27.59 Ω	27.59 Ω
THDI	18.20%	21.35%	24.60%	28.20%	31.98%
THDV	1.20%	1.35%	1.50%	1.66%	1.83%
DPF	99.99%	99.99%	99.99%	99.99%	99.99%
F_{HL}	3.51	4.32	5.24	6.22	7.32
S_{max}	82.44%	78.49%	74.63%	71.08%	67.64%

Table 6: For case 2-6, the results achieved by the optimal passive filter, which is designed according to the traditional approach without considering THDI and THDV constraints.

	Case 2	Case 3	Case 4	Case 5	Case 6
X_{LF}	1.05 Ω	1.04 Ω	1.02 Ω	1.01 Ω	1.00Ω
X_{CF}	27.59 Ω	27.59 Ω	27.59 Ω	27.59 Ω	27.59 Ω
THDI	13.22%	15.25%	17.30%	19.40%	21.37%
THDV	1.46%	1.65%	1.81%	2.00%	2.19%
DPF	99.99%	99.99%	99.99%	99.99%	99.99%
F_{HL}	4.13	5.15	6.26	7.54	9.05
S_{max}	79.38%	74.98%	70.94%	67.01%	63.12%

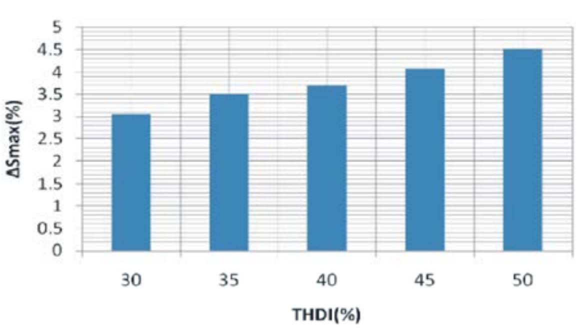

Fig. 3: Calculated ΔS_{max} values for five THDI levels between 30% and 50%.

conditions where there is a highly distorted load current. Figure 3 shows that the difference (ΔS_{max}) of the S_{max} values achieved by the proposed and traditional design approaches increases from 3.06% to 4.52% for the interval of THDI between 30% and 50%.

CONCLUSION

This paper addresses that the passive harmonic filters can be employed to maximize the loading capacity of the transformer supplying a non-sinusoidal load current. To achieve this goal, minimization of F_{HL} index should be taken into account as an objective in the optimal passive filter design problem.

Numerical results show that the proposed optimal design approach is valid for the typical industrial power systems. It is also clearly seen from the results that the proposed design approach provides higher loading capacity of the transformer, which is dedicated to supply a non-sinusoidal load current, when compared with the traditional design approach based on THDI minimization. In addition, the proposed approach has a considerably important advantage on the effective utilization of transformers in the industrial power systems with highly distorted currents.

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Nomenclature:

- $\underline{V}_h$, $\underline{I}_h$: h^{th} harmonic voltage and current phasors,
- V_h, I_h : h^{th} harmonic voltage and current rms values,
- φ_h : Phase angle difference between h^{th} harmonic voltage and current,
- DPF : Displacement power factor,
- THDI : Current total harmonic distortion,
- THDV : Voltage total harmonic distortion,
- P_1 : Fundamental harmonic active power,
- S_1 : Fundamental harmonic apparent power,
- F_{HL} : Harmonic loss factor,
- P_{LL-R} : Transformer's winding rated loss,
- P_{EC-R} : Transformer's winding eddy-current rated loss,
- I_{max} : RMS current capacity of a dry type transformer under non-linear load conditions,
- S_{max} : Loading capacity of a dry type transformer under non-linear load conditions.

Connection type: Star / Star,
Rated power: 2 MVA
Rated voltages of Primary and secondary sides: 6300 V / 400 V,
DC and AC winding losses measured at the rated current: 10.56 kW and 2.438 kW,
Short circuit voltage: 4.5%.

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