

Comparative Evaluation of Various Passive Filter Types Regarding Their Contribution to Transformer's Loading Capacity under Non-Sinusoidal Conditions

Alp Karadeniz¹ and Murat Erhan Balci²

Department of Electrical and Electronics Engineering, Balikesir University, Cagis Campus, Balikesir, Turkey

akaradeniz@balikesir.edu.tr, mbalci@balikesir.edu.tr

Abstract

This study aims to comparatively evaluate several kinds of passive filters by regarding their contribution on the loading capacity of the transformers under non-sinusoidal conditions. For the comparative evaluation, the studied passive filter types are optimally designed to minimize the harmonic loss factor (F_{HL}) index, which is defined as a tool to determine the transformer's permissible loading capacity under non-sinusoidal current conditions in IEEE C.57.110 standard. According to the harmonic distortion limitations and the reactive power compensation level recommended in IEEE 519 standard, the individual and total harmonic distortions of voltage and current at point of common coupling (PCC) and displacement power factor are considered as constraints of the studied optimal filter design problems. The simulation results are provided for the typical industrial power system with background voltage distortion and nonlinear loads.

1. Introduction

Power electronic devices such as ac and dc adjustable speed drives, power rectifiers and inverters, etc. are widely employed to control large power loads in the modern power systems. The loads controlled via power electronic devices, generally called as non-linear loads in the literature, have nonsinusoidal or distorted current wave shapes, which lead to distorted PCC voltages in the system. The distorted voltages and currents may give rise to malfunction and overheating of equipment in the system [1]. To avoid these problems, voltage and current harmonics are mitigated by passive [2] and active filters [3]. Passive filters have less harmonic mitigation capability when compared to active ones. However, they are still used since their low costs [4], [5]. There are five widely implemented passive filters as single-tuned (STF), double-tuned (DTF), triple-tuned (TTF), damped double-tuned (DDTF), first-order high-pass, second-order high-pass and C-type (CTF) filters [2]. Here it should be noted that since first-order and second-order high-pass filters have high fundamental harmonic losses, they are not used alone and are commonly considered in composite filtering schemes.

Optimal design of passive filters is not a straight forward problem. It is clearly reported in [6]-[8] that Current total harmonic distortion (THD_I) minimization, voltage total harmonic distortion ($THDV$) minimization, power factor maximization, the filter's loss minimization and the filter's investment cost minimization are sub-objectives of the traditional optimal filter design approaches.

On the other side, in [9], [10], authors employed STF and CTF designs to maximize the loading capacity of a transformer,

which is dedicated to supply a non-linear load in the typical industrial power system with distorted background voltage. Objective function of both optimal designs is to minimize the harmonic loss factor (F_{HL}) defined in IEEE standard C.57.110 [11]. In addition, by regarding IEEE standard 519 [12], their constraints are chosen as total and individual harmonic distortion limitations of the PCC voltage and line current and desired displacement power factor (DPF) interval.

The main goal of this paper is to comparatively evaluate the widely implemented passive harmonic filters as STF, DTF, TTF, DDTF and CTF by regarding their contribution on the loading capacity of the transformers under non-sinusoidal conditions. The results are simulated for the typical industrial power system, which is firstly introduced in IEEE 519 standard and used as a benchmark system in many works on the optimal passive filter design [6], [8], [9], [10], [13]. It is represented with the harmonic models of the system equipment widely considered in the literature [14]-[16]. The considered optimal filter design problems are solved by using Particle Swarm Optimization (PSO) algorithm, which was used for the solution of optimal passive filter design in several papers [6], [17].

2. Harmonic Modelling of Typical Industrial Power System

Single line diagram of the typical industrial power system is shown in Fig. 1. It consists of a consumer with three-phase linear and non-linear loads, the consumer's transformer, which carry energy from PCC to the consumer, and a passive filter connected to load bus.

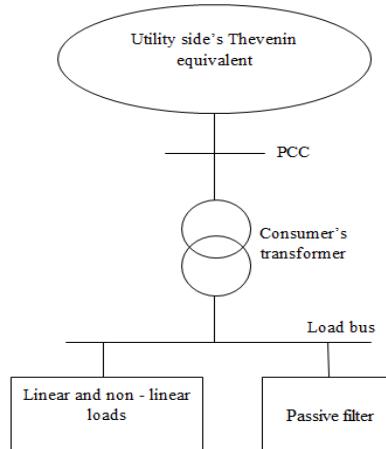


Fig. 1. Single line diagram of the typical industrial power system.

The single-phase equivalent circuit of the system, which is given in **Fig. 2**, can practically be used to write the current, voltage and power expressions for the system. This solution is valid since the system is balanced.

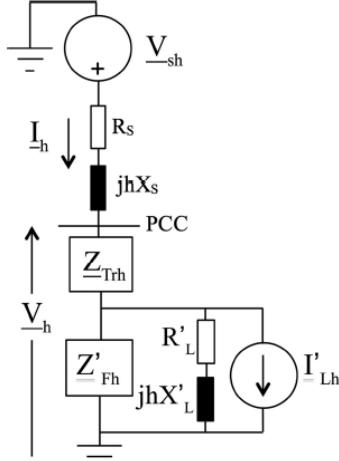


Fig. 2. Single-phase equivalent circuit of the typical industrial power system.

In the same figure, a linear impedance ($R'_L + jhX'_L$) and a constant current source per harmonic (I'_Lh) are the modelling parameters of the linear and non-linear loads [14]-[16], which are referred to the primary side of the transformer. Note that constant current source model is adequate for the representation of the nonlinear loads under the non-sinusoidal voltage with total harmonic distortion (THDV) less than 10% [15]. Utility side is modelled as Thevenin equivalent voltage source (V_{sh}) and Thevenin equivalent impedance ($Z_{sh} = R_s + jhX_s$) for each harmonic order. For the studied system, by considering the milestone studies on the harmonic modelling and simulation [14], [16], the consumer's transformer is practically modelled using its h th harmonic short-circuit impedance, which is referred to its primary side:

$$Z_{Trh} = R_{Trh} + jhX_{Trh} \quad (1)$$

where X_{Tr} is the winding's fundamental harmonic inductive reactance and R_{Trh} denotes the winding's h th harmonic resistance. According to [11], [18] R_{Trh} consists of two parts such as the winding's dc resistance (R_{dc}) and the winding's equivalent resistance corresponding to the eddy-current loss (R_{ec}):

$$R_{Trh} = R_{dc} + h^2 R_{ec} \quad (2)$$

Hence, optimal design of the STF, DTF, TTF, DDTF and CTF will be studied in this paper. Single-phase equivalents of these filters are given in Fig. 3. The h th harmonic impedance of the passive filter, which is referred to the primary side of the transformer, can be expressed as;

$$Z'_{fh} = j \left(hX'_{LF1} - \frac{X'_{CF1}}{h} \right) \quad \text{for STF} \quad (3)$$

$$Z'_{fh} = j \left(hX'_{LF1} - \frac{X'_{CF1}}{h} \right) + \frac{X'_{LF2} X'_{CF2}}{j \left(hX'_{LF2} - \frac{X'_{CF2}}{h} \right)} \quad \text{for DTF} \quad (4)$$

$$Z'_{fh} = j \left(hX'_{LF1} - \frac{X'_{CF1}}{h} \right) + \frac{X'_{LF2} X'_{CF2}}{j \left(hX'_{LF2} - \frac{X'_{CF2}}{h} \right)} + \frac{X'_{LF3} X'_{CF3}}{j \left(hX'_{LF3} - \frac{X'_{CF3}}{h} \right)} \quad \text{for TTF (5)}$$

$$Z'_{fh} = j \left(hX'_{LF1} - \frac{X'_{CF1}}{h} \right) + \frac{1}{\frac{1}{R'_F} + \frac{1}{jhX'_{LF2}} + \frac{1}{-jX'_{CF2}/h}} \quad \text{for DDTF (6)}$$

$$Z'_{fh} = -j \frac{X'_{CF1}}{h} + \frac{R'_F j (hX'_{LF1} - X'_{CF2}/h)}{R'_F + j(hX'_{LF1} - X'_{CF2}/h)} \quad \text{for CTF (7)}$$

By expressing the parallel equivalent of the referred h th harmonic impedance of load ($R'_L + jhX'_L$) and the referred h th harmonic impedance of passive filter (Z'_{fh}) as,

$$Z'_{FLh} = \left(\frac{1}{Z'_{fh}} + \frac{1}{R'_L + jhX'_L} \right)^{-1} \quad (8)$$

and by regarding Superposition principle the line current and PCC voltage can be written for the h th harmonic order:

$$I_h = \frac{V_{sh}}{Z_{sh} + Z_{Trh} + Z'_{FLh}} + \frac{Z'_{FLh}}{Z_{sh} + Z_{Trh} + Z'_{FLh}} I'_{Lh} \quad (9)$$

$$V_h = V_{sh} - I_h Z_{sh} \quad (10)$$

Note that in above mentioned expressions, subscript ($\underline{}$) denotes phasor values of the respective voltage, current and impedances.

THDV and THDI can be calculated as follows:

$$THDV = \frac{\sqrt{\sum_{h \geq 2} V_h^2}}{V_1} \cdot 100 \quad (11)$$

$$THDI = \frac{\sqrt{\sum_{h \geq 2} I_h^2}}{I_1} \cdot 100 \quad (12)$$

where I_1 and I_h are the fundamental and h th harmonic rms currents, and V_1 and V_h are the fundamental and h th harmonic rms voltages.

In terms of fundamental harmonic active power ($P_1 = V_1 I_1 \cos(\phi_1)$) and fundamental harmonic apparent power ($S_1 = V_1 I_1$), displacement power factor (DPF) can be found as:

$$DPF = \frac{P_1}{S_1} \quad (13)$$

Finally, for the line current, the F_{HL} index, which is placed in IEEE std. C57.110, can be written:

$$F_{HL} = \frac{\sum_{h \geq 1} h^2 I_h^2}{\sum_{h \geq 1} I_h^2} \quad (14)$$

Thus, the maximum permissible current capacity (I_{max} (pu)) and the maximum permissible loading capacity (S_{max} (%)) of the dry-type consumer transformer can be calculated as follows;

$$I_{max} (\text{pu}) = \sqrt{\frac{P_{LL-R} (\text{pu})}{1 + F_{HL} P_{EC-R} (\text{pu})}} = \sqrt{\frac{1 + P_{EC-R} (\text{pu})}{1 + F_{HL} P_{EC-R} (\text{pu})}} \quad (15)$$

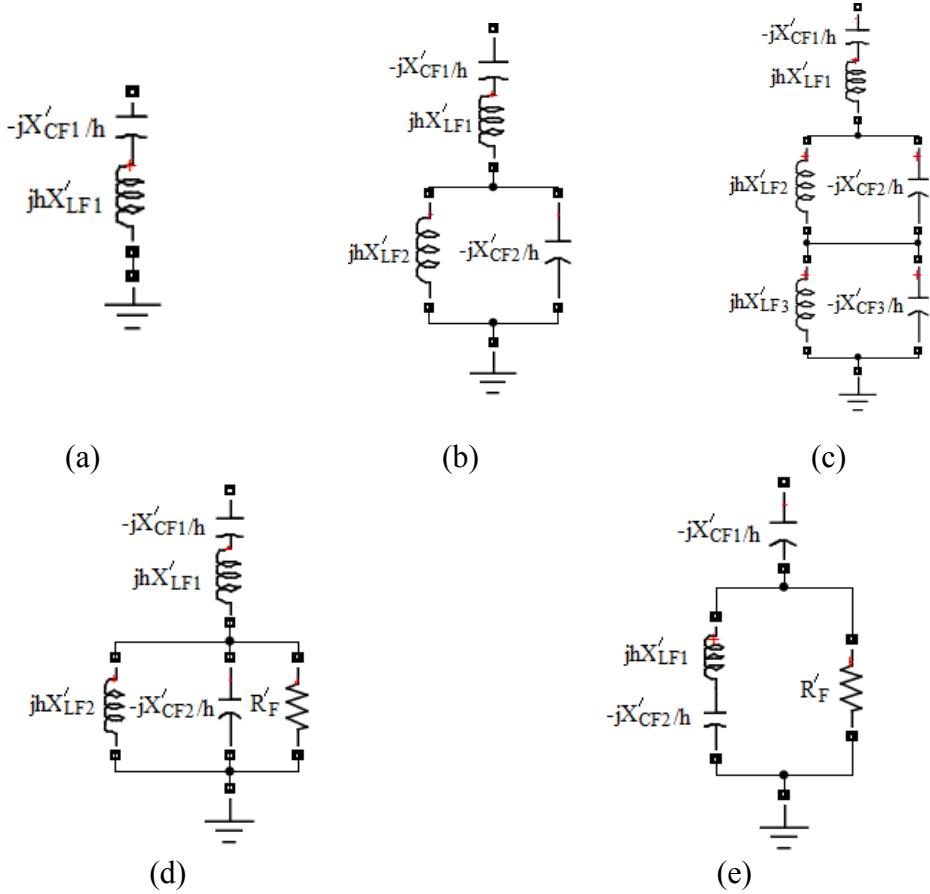


Fig. 3. h/h harmonic single-phase equivalent circuits of (a) STF, (b) DTF, (c) TTF, (d) DDTF and (e) CTF.

$$S_{\max} (\%) = \sqrt{3} V_R (\text{pu}) I_{\max} (\text{pu}) \cdot 100 \quad (16)$$

where $V_R(\text{pu})$, $P_{LL-R}(\text{pu})$ and $P_{EC-R}(\text{pu})$ are pu values of the primary side rated line-to-line voltage, winding rated loss and winding eddy-current rated loss of the consumer's transformer, respectively.

The optimal design problem of the STF, DTF, TTF, DDTF and CTF will be formulated and solved by using the above mentioned modelling issues in the next sections.

3. Problem Formulation and solution algorithm of the Optimal Filter Design Based on F_{HL} Minimization

This paper aims to comparatively evaluate STF, DTF, TTF, DDTF and CTF by regarding their contribution on the loading capacity of the transformers under non-sinusoidal conditions. Reference [9] and [10] shows that minimization of F_{HL} index should be chosen as the objective of the optimal filter designs which aim to maximize the loading capacity of transformers under non-sinusoidal conditions. On the other side, individual harmonics (V_h and I_h) and total harmonic distortions ($THDV$ and $THDI$) of the PCC voltage and line current should be defined as constraints of the optimal filter designs due to the harmonic limitations placed in IEEE std. 519. The same standard also recommends that a lagging DPF should have a value between 95% and 100%. This means that DPF should be considered as the fourth constraint of the optimal designs. Accordingly, for STF, DTF, TTF, DDTF and CTF, the formulation of the optimal design problem can generally be written as follows:

Find: Filter's resistance and reactance parameters (fp),

$$\text{To Minimize } F_{HL}(fp) \quad (17)$$

Subject to

$$V_h(fp) \leq \text{Max}V_h \quad (18)$$

$$I_h(fp) \leq \text{Max}I_h \quad (19)$$

$$THDV(fp) \leq \text{Max}THDV \quad (20)$$

$$THDI(fp) \leq \text{Max}THDI \quad (21)$$

$$95\% \leq DPF(fp) \leq 100\% \text{ lagging} \quad (22)$$

where eq. (17) and eq. (18)-(22) are the objective function and inequality constraints of the problem formulation, respectively. In the inequality constraints, $\text{Max}THDI$ and $\text{Max}THDV$ are the maximum allowable $THDI$ and $THDV$ values, which are placed in IEEE standard 519. $\text{Max}V_h$ and $\text{Max}I_h$ denote the maximum allowable individual harmonic values determined within the same standard. fp denotes: (i) X'_{LF1} and X'_{CF1} for STF, (ii) X'_{LF1} , X'_{CF1} , X'_{LF2} and X'_{CF2} for DTF, (iii) X'_{LF1} , X'_{CF1} , X'_{LF2} , X'_{CF2} , X'_{LF3} and X'_{CF3} for TTF, (iv) X'_{LF1} , X'_{CF1} , X'_{LF2} , X'_{CF2} and R'_F for DDTF and (v) X'_{LF1} , X'_{CF1} , X'_{CF2} and R'_F for CTF.

PSO algorithm is employed to find optimal parameters of the studied filter types with respect to the problem formulation given above. This algorithm was severally implemented to solve

optimal passive filter design problem. Readers could refer to [6], [17] for detailed information about the solution of the optimal filter design problems using the PSO algorithm.

4. Analysis Results

In this section, numerical results, which are obtained by simulating the typical industrial power system, will be presented to comparatively evaluate the filters' contribution on the transformer's loading capacity under nonsinusoidal conditions. Fundamental frequency supply voltage and short-circuit power of the simulated system are 6.35 kV (line-to-line) and 210 MVA. For the simulated system's single-phase equivalent circuit, the source impedance parameters and the load impedance parameters, which are referred to the primary side of the transformer, are $R_S = 0.0189 \Omega$, $X_S = 0.189 \Omega$, $R'_L = 13.85 \Omega$

and $X'_L = 13.18 \Omega$. The system has a star-star connected consumer transformer with the nameplate ratings such as 2 MVA and 6300 V/ 400 V. R_{dc} , R_{ec} and X_{Tr} parameters of the transformer are 0.104Ω , 0.024Ω and 0.882Ω , respectively. The rest of the properties of the consumer's transformer can be found in [10].

For the simulated system, the voltage source harmonics and the current source harmonics, which are referred to the primary side of the transformer, are presented in Table 1. For the simulated system, the $THDV$, $THDI$ and F_{HL} values at the PCC bus are 2.32%, 8.58% and 3.70, respectively. The system has DPF and P_I values as 70.51% and 1410 kW. S_{max} is 81.47% for the transformer under the simulated conditions. IEEE std. 519 recommends the voltage and current harmonic limits, which are given in Table 2, for the exemplary system.

Table 1: For the simulated system, the voltage source harmonics and the current source harmonics, which are referred to the primary side of the transformer.

h	$V_{Sh} (V)$	$I'_{Lh} (A)$
5	$36.64 \angle 0^\circ$	$7.63 \angle 5^\circ - 45^\circ$
7	$27.48 \angle 0^\circ$	$7.04 \angle 7^\circ - 45^\circ$
11	$23.82 \angle 0^\circ$	$6.45 \angle 11^\circ - 45^\circ$
13	$20.15 \angle 0^\circ$	$5.87 \angle 13^\circ - 45^\circ$
17, 19, 23, 25	$11.00 \angle 0^\circ$	$4.11 \angle h^\circ - 45^\circ$
29, 31, 35, 37	$3.66 \angle 0^\circ$	$2.93 \angle h^\circ - 45^\circ$
41, 43, 47, 49	$1.85 \angle 0^\circ$	$1.76 \angle h^\circ - 45^\circ$

Table 2: The IEEE std. 519 harmonic limits for the exemplary system.

	Individual harmonic distortion limits (percent of the fundamental harmonic)					THD limits
	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	
Line Current	12.0	5.5	5.0	2.0	1.0	15.0
PCC Voltage			3.0			5.0

Table 3: The parameters of the optimal filter designs.

	STF	DTF	TTF	DDTF	CTF
$X'_{CF1} (\Omega)$	27.960	27.960	27.960	27.960	27.960
$X'_{CF2} (\Omega)$	-	27.960	27.960	80.399	1.393
$X'_{CF3} (\Omega)$	-	-	18.477	-	-
$X'_{LF1} (\Omega)$	0.715	0.256	0.163	0.236	1.393
$X'_{LF2} (\Omega)$	-	0.523	0.497	0.890	-
$X'_{LF3} (\Omega)$	-	-	0.093	-	-
$R'_F (\Omega)$	-	-	-	7.135	6.882

Table 4: The power quality quantities measured at PCC and maximum loading capacities of the transformer for the optimal filter designs.

	STF	DTF	TTF	DDTF	CTF
THDI(%)	11.373	6.150	5.866	5.974	7.515
THDV(%)	1.425	1.588	1.570	1.606	1.609
DPF(%)	99.987	99.991	99.988	99.999	99.918
F_{HL}	1.948	1.286	1.170	1.244	1.369
S_{max}(%)	92.140	97.420	98.442	97.790	96.700

For the system, the optimal design problems of the studied filter types are solved by PSO algorithm. The parameters of the optimal filter designs are presented in Table 3, and the power quality indices and maximum transformer loading capacities achieved by the optimal filter designs are given in Table 4. It is seen from Table 4 that all filters provides DPF values around 99.9% and $THDV$ values around 1.5%. It is observed that for STF, DTF, TTF, DDTF and CTF, respective $THDI$ values are 11.373%, 6.150%, 5.866%, 5.974% and 7.515%, respective F_{HL} values are 1.948, 1.286, 1.170, 1.244 and 1.369, and respective S_{max} values are 92.140%, 97.420%, 98.442%, 97.790% and 96.700%. Thus, the difference between the highest and lowest values of the transformer's loading capacity, which are achieved by TTF and STF, is around 6.3%.

5. Conclusion

This study aims to comparatively evaluate the widely known five passive harmonic filters as single-tuned (STF), double-tuned (DTF), triple-tuned (TTF), damped double-tuned (DDTF) and C-type (CTF) filters by regarding their contribution on the loading capacity of the transformers under non-sinsuoidal conditions.

It can clearly be concluded from the simulated results that TTF, DDTF and DTF provides higher S_{max} values than STF and CTF, which are previously considered for the effective utilization of transforms under nonsinusoidal conditions in the literature. In addition, the highest and lowest maximum loading capacity values of the transformer are achieved by TTF and STF, respectively. It should also be mentioned from the results that kind of the filter can considerably affect the improvement of the transformer's loading capacity.

6. References

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7. Acknowledgement

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