Optimal Passive Filter Design for Effective Utilization of Cables and Transformers under Non-sinusoidal Conditions

Shady H. E. Abdel Aleem
Member, IEEE
15th of May Higher Institute of Engineering
Cairo, Egypt
engyshady@ieee.org

Murat E. Balci
Member, IEEE
Balikesir University
Balikesir, Turkey
mbalci@balikesir.edu.tr

Ahmed F. Zobaa
Senior Member, IEEE
School of Engineering and Design, Brunel University,
UB8 3PH Uxbridge, U.K
azobaa@ieee.org

Selcuk Sakar
Gediz University
Izmir, Turkey
selcuk.sakar@gediz.edu.tr

***Abstract*— Transformers and cables have overheating and reduced loading capabilities under non-sinusoidal conditions due to the fact that their losses increases with not only rms value but also frequency of the load current. In this paper, it is aimed to employ passive filters for effective utilization of the cables and transformers in the harmonically contaminated power systems. To attain this goal, an optimal passive filter design approach is provided to maximize the power factor definition, which takes into account frequency-dependent losses of the power transmission and distribution equipment, under non-sinusoidal conditions. The obtained simulation results show that the proposed approach has a considerable advantage on the reduction of the total transmission loss and the transformer loading capability under non-sinusoidal conditions when compared to the traditional optimal filter design approach, which aims to maximize classical power factor definition. On the other hand, for the simulated system cases, both approaches lead to almost the same current carrying (or loading) capability value of the cables.**

***Index Terms*—Transformers, cables, loading capability, C-type filters, harmonic distortion, optimal filter design.**

I. Introduction

Present day's power systems invariably have nonlinear loads, which inject harmonics into the system and give rise to non-sinusoidal voltages and currents. Accordingly, in the literature, considerable interests have been focused on the adverse effects of the harmonics on the power distribution equipment such as cables [1]-[4] and transformers [5]-[9]. These studies reveal that the resistances of the cables and the winding resistances of the transformers increase with the frequency. Due to this, cables and transformers have excessive losses under distorted (or non-sinusoidal) current conditions even if the rms values of the distorted currents delivered by them are lower than their sinusoidal rated currents. As a result, the distorted currents cause the reduction of the useful life of transformers and cables. To avoid this problem, cables and transformers should be derated under non-sinusoidal current conditions [4], [9]. Derating factor (maximum permissible current carrying or loading capability) can basically be interpreted as the ratio between the non-sinusoidal load current's rms value, which causes the rated loss of the equipment (transformer or cable), and the equipment's rated sinusoidal current.

Power factor is an indicator of how effectively are utilized the power transmission and distribution equipment in the power systems [10]. *Accordingly,* maximization of the classical power factor (*PF*) is traditionally handled for optimal passive filter design in the literature [11]-[13]. However, [15] clearly interprets that maximization of classical power factor definition, which is calculated by regarding active power and classical apparent power, does not provide the minimum loss condition of a power system having transmission lines with frequency-dependent resistances under nonsinusoidal conditions.

This study aims to employ passive filters for effective utilization of the transformers and cables, of which the losses are considerably frequency-dependent, under non-sinusoidal conditions. To achieve this aim, an optimal passive filter design approach is developed to maximize the power factor expression [15], which considers frequency dependent loss of the power system equipment, in non-sinusoidal power systems. The C-type filter is used for the demonstration of the proposed approach since it provides good filtering performance and reduced fundamental frequency loss when compared to other types of the filters [13].

This paper is organized as follows, on which the present context forms Section I as an introduction to the work. Section II is devoted to the modeling of the studied system. Section III gives the problem formulations of the proposed and the traditional optimal design approaches. The numerical

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results obtained with two approaches are discussed in Section IV. The conclusion is presented in Section V.

II. MODELING OF THE STUDIED SYSTEM

One-line diagram of the studied system, which is considered in various works [11]-[13], [16], is given in Fig. 1. It has a consumer with three-phase linear and non-linear loads, the consumer's transformer & cable, which carry energy from PCC to the load bus, and a C-type filter connected to the load bus. It should be mentioned that in the studied system, some of the linear loads are individually compensated with the basic capacitors.

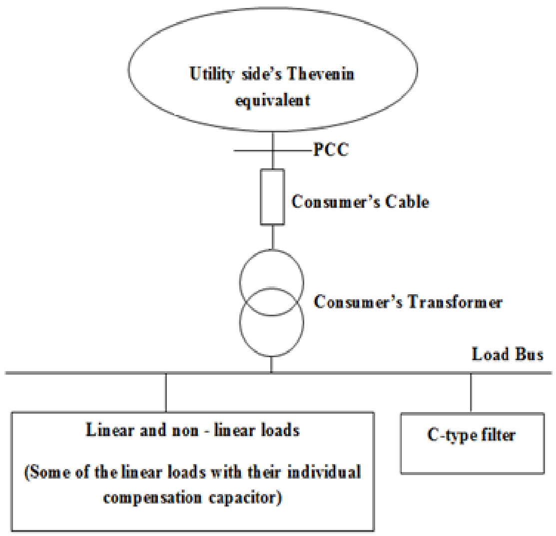

Fig. 1: One-line diagram of the studied system.

To write the current, voltage and power expressions for the system, its single-phase equivalent circuit given in Fig. 2 can be derived since the system is balanced. As shown in this 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 [17], which are referred to the primary side of the transformer, where h is the harmonic number. The referred hth harmonic impedance of the individual compensation capacitor, which is preinstalled in the consumer side, is denoted by $-jX'_{Ci}/h$. Utility side is modelled as Thevenin equivalent voltage source ($\underline{V}_{Sh}$) and Thevenin equivalent impedance ($\underline{Z}_{Sh}$) for each harmonic order. By regarding the skin effect, the hth harmonic resistance (R_{Sh}) of the Thevenin equivalent impedance and the hth harmonic resistance (R_{CBh}) of the cable impedance ($\underline{Z}_{CBh}$) can be written as $R_{Sh} = R_S\sqrt{h}$ and $R_{CBh} = R_{CB}\sqrt{h}$ where R_S and R_{CB} are the fundamental harmonic ac resistances of the supply lines and cables, respectively. In addition, the hth harmonic inductive reactances of the supply lines and cables can be expressed as $X_{Sh}=hX_S$ and $X_{CBh}=hX_{CB}$, respectively.

With respect to [17], the consumer's transformer is practically modelled using its hth harmonic short-circuit impedance, which is referred to its primary side:

$$\underline{Z}_{TRh} = R_{TRh} + jhX_{TR} \tag{1}$$

where X_{TR} is the winding's fundamental harmonic inductive reactance and R_{TRh} denotes the winding's hth harmonic resistance. R_{TRh} consists of two parts such as the winding's dc resistance (R_{TRdc}) and the winding's equivalent resistance corresponding to the eddy-current loss (R_{TRec}) [5], [6]:

$$R_{TRh} = R_{TRdc} + h^2 R_{TRec} \tag{2}$$

Fig. 3 shows that single-phase circuit representation of the C-type filter. It has the main capacitor (X_{CF1}) in series with a parallel connection of the inductor (X_{LF})-capacitor (X_{CF2}) branch and damping resistor (R_F). Since the C-type filter behaves as the main capacitor for fundamental frequency, the reactance values of the series connected inductor and capacitor are equal to each other ($X_{LF}=X_{CF2}=X_F$). Thus, the hth harmonic impedance of the filter referred to the primary side of the transformer can be expressed as;

$$\underline{Z}'_{Fh} = a^2\left(-j\frac{X_{CF1}}{h} + \frac{jR_F X_F\left(h^2-1\right)}{hR_F + jX_F\left(h^2-1\right)}\right) \tag{3}$$

where a is the ratio of primary and secondary voltages of the transformer.

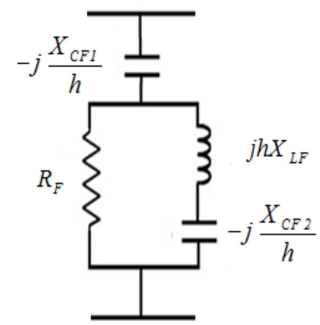

Fig. 3: Single-phase circuit of the C-type filter.

According to the above mentioned modeling issues, for hth harmonic order, line current, PCC voltage and load bus voltage, which is referred to the transformer's primary side, can be written by means of superposition principle:

$$\underline{I}_h = \frac{\underline{V}_{Sh}}{\underline{Z}_{Sh} + \underline{Z}_{CBh} + \underline{Z}_{TRh} + \underline{Z}'_{FLh}} + \frac{\underline{Z}'_{FLh}}{\underline{Z}_{Sh} + \underline{Z}_{CBh} + \underline{Z}_{TRh} + \underline{Z}'_{FLh}}\underline{I}'_{Lh} \tag{4}$$

$$\underline{V}_h = \underline{V}_{Sh} - \underline{I}_h\underline{Z}_{Sh}, \quad \underline{V}'_{Lh} = \underline{V}_{Sh} - \underline{I}_h\left(\underline{Z}_{Sh} + \underline{Z}_{CBh} + \underline{Z}_{TRh}\right) \tag{5}$$

where $\underline{Z}'_{FLh}$ is the parallel equivalent of the load's hth harmonic impedance, individual compensation capacitor's reactance and C-type filter's hth harmonic impedance, which are referred to the transformer's primary side. Note that $\underline{Z}'_{FLh}$ can be calculated as;

$$\underline{Z}'_{FLh} = \left(\frac{1}{\underline{Z}'_{Fh}} + \frac{1}{R'_L + jhX'_L} + j\frac{h}{X'_{Ci}}\right)^{-1} \tag{6}$$

Here it should be mentioned that subscript (_) denotes phasor values of the respective voltage, current and impedances.

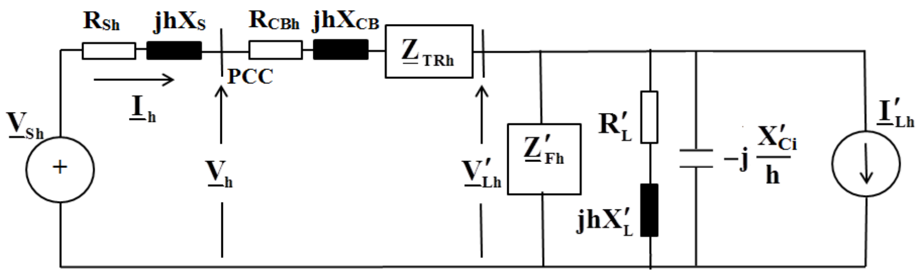

Fig. 2: Single-phase equivalent circuit of the studied system

$$THDV = \frac{\sqrt{\sum_{h\geq 2} V_h^2}}{V_1}\cdot 100\ , \quad THDI = \frac{\sqrt{\sum_{h\geq 2} I_h^2}}{I_1}\cdot 100 \tag{7}$$

In addition, the displacement power factor (*DPF*) and classical power factor (*PF*) measured at the load bus and the total transmission loss (ΔP_{Total}) can be expressed as

$$DPF = \frac{P_1}{S_1} = \frac{3V'_{L1} I_1 \cos\varphi_1}{3V'_{L1} I_1}, \; PF = \frac{P}{S} = \frac{3\sum_h V'_{Lh} I_h \cos\varphi_h}{3\sqrt{\sum_h (V'_{Lh})^2}\sqrt{\sum_h I_h^2}} \tag{8}$$

$$\Delta P_{Total} = 3\sum_h I_h^2 R_{Lineh} \tag{9}$$

where R_{Lineh} is hth harmonic total line resistance ($R_{Lineh} = R_{Sh} + R_{CBh} + R_{TRh}$).

On the other hand, with respect to the apparent power definition presented in [15];

$$S_e = 3V_e I_e = 3\sqrt{\sum_h \left(\sqrt{\frac{R}{R_{Lineh}}} V'_{Lh}\right)^2}\sqrt{\sum_h \left(\sqrt{\frac{R_{Lineh}}{R}} I_h\right)^2} \tag{10}$$

the power factor at the load bus can be calculated as:

$$PF_e = \frac{P}{S_e} \tag{11}$$

where R is a reference resistance, which can practically be assumed as any value.

Finally, regarding [2] and [9], for the cables and the dry-type transformer employed in the studied system, derating factor values (or the maximum permissible rms current values in percent of the rated current) can be calculated with the expressions given below:

$$DF_{CB}(\%) = \left(1 + \sum_{h\geq 2}\left(\frac{R_{CBh}}{R_{CB}}\right)\left(\frac{I_h}{I_{Base}}\right)^2\right)^{-0.5}\cdot 100 \text{ for cables} \tag{12}$$

$$DF_{TR}(\%) = \sqrt{\frac{1+\Delta P_{EC-R}(pu)}{1+F_{HL}\Delta P_{EC-R}(pu)}}\cdot 100 \text{ for transformer} \tag{13}$$

In (12), I_{Base} is the base current that should be considered as fundamental harmonic component of the load current, and in (13), F_{HL} denotes the harmonic loss factor:

$$F_{HL} = \sum_h h^2 \left(\frac{I_h}{I_1}\right)^2 \Bigg/ \sum_h \left(\frac{I_h}{I_1}\right)^2 \tag{14}$$

The proposed optimal filter design approach based on maximization of PF_e and the traditional optimal filter design approach based on maximization of *PF* will be formulated and solved regarding the above detailed model of the studied system in the next sections.

III. Problem Formulations of The Traditional and The Proposed Optimal Design Approaches

The problem formulations of the traditional and the proposed optimal design approaches are presented in this section.

A. Traditional design approach

PF is traditionally used as an indicator of how effectively are utilized the power transmission and distribution equipment in the power systems. Accordingly, maximization of *PF* has widely been considered as an objective for optimal design of the passive filters [11]-[14]. In addition, desired *DPF* interval and total harmonic distortion (*THDV* and *THDI*) limitations recommended by IEEE std. 519-1992 [18] are generally regarded as three constraints of the traditional optimal filter design approach. Therefore, according to the traditional approach, optimal design problem of the C-type filter can be formulated as follows:

$$\text{Maximize } PF(R_F, X_{CF1}, X_F) \tag{15}$$

Subjected to:

$$THDV(R_F, X_{CF1}, X_F) \leq MaxTHDV \tag{16}$$

$$THDI(R_F, X_{CF1}, X_F) \leq MaxTHDI \tag{17}$$

$$95\% \leq DPF(R_F, X_{CF1}, X_F) \leq 100\% \tag{18}$$

where Equation (15) and Equations (16)-(18) are the objective function and inequality constraints of the problem formulation, respectively. In the inequality constraints, *MaxTHDI* and *MaxTHDV* are the maximum allowable *THDI* and *THDV* values, which are stated in IEEE standard 519.

B. Proposed design approach

As mentioned before, the proposed approach handles maximization of PF_e as an objective for the optimal filter design problem. Thus, by regarding the inequality constraints given in eq. (16)-(18), the problem formulation of the proposed approach can be written as;

$$\text{Maximize } PF_e(R_F, X_{CF1}, X_F) \tag{19}$$

Subjected to:

The inequality constraints given in (16)-(18)

Above detailed optimal filter design problems are solved via FORTRAN feasible sequential quadratic programming (FFSQP) [19]. FFSQP was successfully employed to design the optimal passive filters in several studies [16], [20], [21]. Readers could refer to [16], [19] and [20] for much information about the optimal filter design solution algorithm based on FFSQP.

IV. NUMERICAL RESULTS

In this section, the proposed and traditional optimal design approaches are numerically evaluated for two cases (Case 1 and 2) of the studied system with the cable types [22], which are detailed in Table I. These cable lines have the same lengths and current carrying capabilities (for sinusoidal current condition) such as 0.1 km and 640 A, respectively. Fundamental frequency supply voltage and short-circuit power of two simulated cases are predetermined as 6350 V (line-to-line) and 800 MVA. For the studied system's single-phase equivalent circuit, the impedance parameters of the source and load sides are $R_S = 0.0038\ \Omega$, $X_S = 0.0506\ \Omega$, $R'_L = 4.00\ \Omega$, $X'_L = 4.05\ \Omega$ and $X'_{Ci} = 100.00\ \Omega$. The system consists of a star-star connected consumer transformer with the nameplate ratings such as 7 MVA and 6300 V/ 400 V. The transformer's winding impedance parameters are $R_{TRdc} = 0.026\ \Omega$, $R_{TRec} = 0.006\ \Omega$ and $X_{TR} = 0.221\ \Omega$. The voltage source harmonics and the current source harmonics referred to the primary side of the transformer are presented in Table II.

TABLE I
PROPERTIES OF CABLE TYPES SIMULATED IN STUDIED SYSTEM

Cases	Cable Type	R_{CB} (Ω/km)	X_{CB} (Ω/km)
1	6.35 kV, Trefoil formation, PVC insulated, Unarmoured, Single core copper wire 240 mm^2 cross sectional area	0.098	0.1037
2	6.35 kV, Flat spaced formation, PVC insulated, Unarmoured, Single core aluminium wire, 240 mm^2 cross sectional area	0.161	0.1634

TABLE II
VOLTAGE SOURCE HARMONICS AND CURRENT SOURCE HARMONICS REFERRED TO TRANSFORMER'S PRIMARY SIDE

h	$\bar{V}_{Sh}$ (V)	$\bar{I}'_{Lh}$ (A)
5	$55.00\angle 0^\circ$	$75.00\angle -5\cdot 45^\circ$
7	$40.00\angle 0^\circ$	$65.00\angle -7\cdot 45^\circ$
11	$35.00\angle 0^\circ$	$55.00\angle -11\cdot 45^\circ$
13	$30.00\angle 0^\circ$	$40.00\angle -13\cdot 45^\circ$
17, 19, 23, 25	$25.00\angle 0^\circ$	$15.00\angle -h\cdot 45^\circ$
29, 31, 35, 37	$12.50\angle 0^\circ$	$10.00\angle -h\cdot 45^\circ$
41, 43, 47, 49	$7.50\angle 0^\circ$	$7.50\angle -h\cdot 45^\circ$

For both cases of the uncompensated system, *THDV* and *THDI* values measured at the PCC, power factors and powers measured at the load bus, normalized value of the total transmission loss (ΔP_{Total}) and loading capabilities (DF_{CB} and DF_{TR}) of the cable and transformer can be seen in Table III. Normalized value of the total transmission loss is calculated by regarding the total transmission loss under the sinusoidal rated current condition as base power. This table shows that for Case 1 and 2, the active power values (P) drawn by the loads are about 4.5 MW. For Case 1, *THDV*, *THDI*, *PF*, PF_e, S and S_e are 3.812%, 25.686%, 69.022%, 48.783%, 6.586 MVA and 9.319 MVA, respectively. On the other hand, for Case 2, *THDV*, *THDI*, *PF*, PF_e, S and S_e have the values as 3.824%, 25.840%, 68.927%, 50.011%, 6.574MVA and 9.060 MVA, respectively. Under Case 1 and 2, the transformer has dramatically reduced loading capabilities (DF_{TR}) around 64%. In addition, the cables have reduced current carrying capacities (DF_{CB}) about 91%. The normalized value of the total transmission loss (ΔP_{Total}) has considerably high values as 1.887 and 1.789 in Case 1 and 2 of the uncompensated system, respectively.

TABLE III
POWER QUALITY INDICES AND POWER QUANTITIES FOR TWO CASES OF UNCOMPANSATED SYSTEM

	Case 1	Case 2
P (MW)	4.546	4.531
S (MVA)	6.586	6.574
S_e (MVA)	9.319	9.060
DF_{TR} (%)	64.106	63.94
DF_{CB} (%)	91.111	91.014
THDV (%)	3.812	3.824
THDI (%)	25.686	25.840
PF (%)	69.022	68.927
PF_e (%)	48.783	50.011
ΔP_{Total}(normalized)	1.887	1.789

For both cases of the system, the results of the proposed and traditional optimal filter design approaches are presented in Table IV and Table V. It can be seen from these tables that for Case 1 and 2, the traditional approach attains higher *PF* values (98.964% and 98.982%) than the proposed one. Since the proposed approach aims to provide maximum PF_e values (89.611% and 90.625%), it achieves considerably lower normalized ΔP_{Total} values (0.621 and 0.606) than the traditional approach. Both approaches achieve *DPF* values higher than 99%.

For Case 1, the proposed approach provides higher DF_{TR} value (88.573%) than the traditional approach achieving DF_{TR} value as 85.036%. In addition, for Case 2, proposed one gives higher DF_{TR} value (88.727%) when compared to the traditional one having DF_{TR}= 85.471%. On the other hand, for Case 1 and 2, both approaches result in almost the same DF_{CB} value just above 97%.

Finally, for Case 1 and 2, the *THDV* values achieved by the proposed approach (around 2.67%) are slightly lower than the *THDV* values achieved by the traditional approach (around 2.71%). The *THDI* values observed for the proposed approach (nearly 14.5%) is larger than the *THDI* values observed for the traditional one (nearly 13%) in the simulated cases of the system. At this point, it should be mentioned that both approaches meet the *THDV* and *THDI* limits recommended by IEEE std. 519.

TABLE IV
THE RESULTS OBTAINED WITH THE PROPOSED APPROACH

	Case 1	Case 2
X_{CF1} (Ω)	0.0307	0.0312
X_F (Ω)	0.0013	0.0013
R_F (Ω)	0.0116	0.0117
DF_{TR} (%)	88.573	88.727
DF_{CB} (%)	97.314	97.379
THDV (%)	2.674	2.675
THDI (%)	14.525	14.347
DPF (%)	99.240	99.359
PF (%)	98.190	98.325
PF_e (%)	89.611	90.625
ΔP_{Total}(normalized)	0.621	0.606

TABLE V
THE RESULTS OBTAİNED BY THE TRADITIONAL APPROACH

	Case 1	Case 2
X_{CF1} (Ω)	0.0345	0.0345
X_F (Ω)	0.0015	0.0015
R_F (Ω)	0.0203	0.0198
DF_{TR} (%)	85.036	85.471
DF_{CB} (%)	97.514	97.569
THDV (%)	2.714	2.715
THDI (%)	13.081	12.960
DPF (%)	99.991	99.991
PF (%)	98.964	98.982
PF_e (%)	87.635	89.008
ΔP_{Total}(normalized)	0.643	0.622

V. CONCLUSION

An optimal passive filter design approach is developed to maximize the power factor expression, which takes into account frequency-dependent losses of the power transmission and distribution equipment, under non-sinusoidal conditions.

Presented simulation results clarify that the proposed approach has a considerable advantage on the reduction of the total transmission loss and the transformer loading capability under non-sinusoidal conditions when compared to the traditional optimal filter design approach, which aims to maximize classical power factor definition. On the other hand, for the simulated system cases, both approaches lead to almost the same current carrying capability value of the cables.

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