A Filter Design Approach to Maximize Ampacity of Cables in Nonsinusoidal Power Systems

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Abstract **— This paper presents an optimal design of the *C*-type passive filters for the effective utilization of the power cables under nonsinusoidal conditions based on maximization of the harmonic derating factor (HDF) of a power cable, where maintaining the load true power factor at an acceptable range is desired. According to IEEE Standard 519, the total harmonic distortions of the voltage and current measured at the point of common coupling are taken into account as main constraints of the proposed approach. The presented numerical results show that the proposed approach provides higher current carrying capacity, or ampacity of the cables under nonsinusoidal conditions when compared to the traditional approaches based on minimization of the current total harmonic distortion and maximization of the true load power factor. A numerical case study is presented to demonstrate the proposed approach.**

Keywords **— Cables, harmonic distortion, reactive power compensation, passive filters.**

I. Introduction

Harmonic currents generated by nonlinear loads can lead to many power quality problems including overheating of transformer and power cables [1]-[4], poor power factor [5]-[7] and the resonance may occur [8]. To prevent overheating of the power cables, they should be derated under harmonically contaminated load current conditions. Derating is the intentional reduction of current carrying capacity (or ampacity) of the power cables by considering the harmonic derating factor (HDF) [4].

Generally, the industrial facilities employ passive and/or active filters for damping of voltage and current harmonic distortion and power factor improvement [8]. Among several kinds of harmonic filters, shunt passive filters are the most commonly preferred ones because of their simplicity and low cost [9]. Besides, optimal harmonic shunt passive filter designs traditionally aim to minimize current total harmonic distortion [10] and/or maximize power factor [11], [12]. In these studies, the desired power factor (PF) range and total harmonic distortion limits recommended by IEEE Standard 519-2014 [13] are considered as the mandatory constraints of the optimal design approaches.

In this study, an optimal filter design approach is proposed to maximize harmonic derating factor (HDF), which is defined to measure maximum permissible ampacity value of the power cables under harmonically contaminated load currents in [4]. Thus, the proposed design approach is useful for effective utilization of power cables in the power systems with the nonlinear loads.

The proposed optimal design approach can be implemented for any kinds of the passive shunt filter. In addition, due to the fact that the C-type passive filter topology has a good harmonic suppression at their tuned frequencies and can damp series and or parallel resonance that may occur [14]-[17], it is preferred for the demonstration of the proposed optimal design approach.

This paper is organized as follows, Section II is committed for the maximum ampacity calculation of the power cables based on HDF. Section III presents the proposed model of the studied system with the *C*-type passive filter beside the necessary equations of sizing its parameters, Section IV gives the problem formulations of the proposed optimal filter design approach based on the maximization of HDF and two traditional design approaches based on PF maximization and THDI minimization. The numerical results obtained with the optimal design approaches are discussed in Section V. The conclusion is presented in Section VI.

II. The Cable Ampacity Calculation in Terms of HDF [4]

Reference [4] introduced a simple general method, which can be used for calculating the maximum permissible ampacity of a cable in the presence of current harmonics. The method can be implemented as follows:

Firstly, assume a distorted line current I_h that contains harmonics of order h, one can describe it using a sequence called harmonic signature (HS) as follows:

$$HS = \left(I_1, \alpha_1 = 1, \alpha_2 = \frac{I_2}{I_1} \ldots \alpha_h = \frac{I_h}{I_1} \right) \tag{1}$$

where I_1 is the fundamental component of the current and $\alpha_1..\alpha_h$ represents the hth per unit harmonic signature of the current.

Secondly, if R_{B1} and R_{Bh} denote fundamental harmonic and hth harmonic AC resistance of the cable including both skin and proximity effects, one can define the hth harmonic normalized AC resistance factor β as follows:

$$\beta_h = \frac{R_{Bh}}{R_{B1}} \qquad (2)$$

Finally, it should be considered that the loss of the cable under a nonsinusoidal current should not exceed its sinusoidal rated loss for avoiding the overheating. Accordingly, by rearranging the expression given in (3), HDF can be written as in (4):

$$I_R^2\left(R_{B1}\right) = I_1^2\left(R_{B1}\right) + I_2^2\left(R_{B2}\right) + \ldots + I_h^2\left(R_{Bh}\right)$$

$$\frac{I_R^2}{I_1^2} = \left(1 + \alpha_2^2\left(\beta_2\right) + \ldots + \alpha_h^2\left(\beta_h\right)\right) \qquad (3)$$

$$HDF = \frac{I_1}{I_R} = \frac{1}{\sqrt{\left(1 + \sum_{h\geq 2}\alpha_h^2\left(\beta_h\right)\right)}} \qquad (4)$$

As a result, the maximum permissible ampacity or maximum current carrying capability (I_{Max}) of a power cable can be determined in terms of HDF under the harmonically distorted load current conditions as follows:

$$I_{\text{Max}} = I_R \cdot HDF \qquad (5)$$

In addition, the maximum three-phase power, which can be delivered by the cable, is found as:

$$S_{\text{Max}} = 3V_L I_R \cdot HDF \qquad (6)$$

where V_L is the true rms value of line-to-neutral voltage measured at the load bus.

III. Modelling of the System under Study

Figure 1 shows the single-line diagram of the system under study. It has a consumer with three-phase linear and nonlinear loads, the consumer's power cable, which carry energy to the loads, and a C-type passive filter connected to load bus.

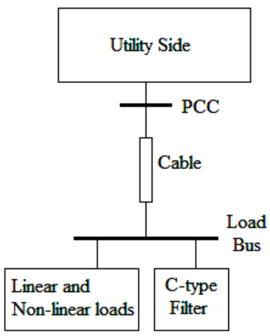

Fig. 1. Single-line diagram of the studied system.

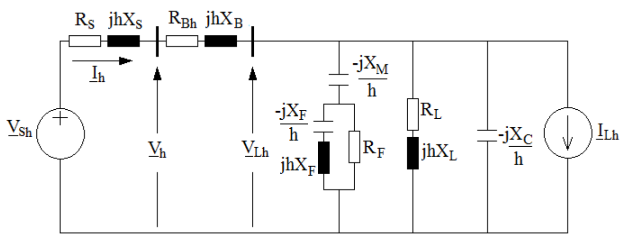

Fig. 2. Single-phase equivalent circuit of the studied system.

In the studied system, some of the linear loads are individually compensated with the basic capacitors. Since the system has balanced voltages and currents; the single-phase equivalent circuit, given in Figure 2, can be used for the simulation of the system. In the single-phase equivalent circuit, the utility side is represented as Thevenin equivalent voltage source ($\underline{V}_{Sh}$) and Thevenin equivalent impedance (R_S+jhX_S) for hth harmonic order. Linear loads with the individual compensation capacitors are modeled as parallel connection of the hth harmonic impedances as R_L+jhX_L and –jX_C/h. Constant current source model ($\underline{I}_{Lh}$) is employed to simulate the nonlinear loads due to the fact that it is the most practical nonlinear load model [18], [19]. Moreover, regarding the skin effect, the cable is represented as hth harmonic impedance ($Z_{Cable,\,h}$) as

$$Z_{Cable,h} = R_{Bh} + jX_{Bh}$$
$$= R_{B1}\sqrt{h} + jhX_{B1} \qquad (7)$$

where R_{B1} and X_{B1} represents the fundamental harmonic resistance and inductive reactance values of the cable.

Figure 3 shows representation of the single-phase circuit of the C-type filter [14]-[17]. It consists of the main capacitor (X_M) in series with a parallel connection of series inductor (X_{LF})-capacitor (X_{CF}) branch and damping resistor (R_F). The main capacitor supplies the loads with the required fundamental reactive power to attain the desired displacement power factor (DPF) value. In the C-type filtering topology, the series inductor-capacitor branch should be tuned to fundamental frequency for avoiding fundamental joule losses. This means that fundamental frequency reactance values of the series connected inductor and the auxiliary capacitor are equal to each other (X_{CF}=X_{LF}=X_F for h=1). The value of the damping parallel resistor is an important parameter to ensure the required performance and effectiveness of the proposed filter.

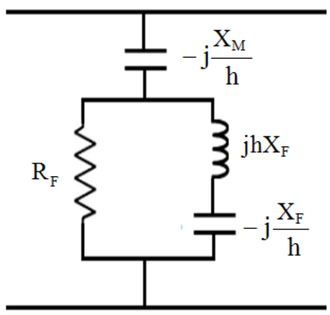

Fig. 3. Single-phase circuit of the C-type filter.

The hth harmonic impedance of the C-type filter can be defined as follows:

$$\underline{Z}_{Ch} = -j\frac{X_M}{h} + \frac{jR_F X_F\left(h^2 - 1\right)}{hR_F + jX_F\left(h^2 - 1\right)} \qquad (8)$$

For the equivalent circuit shown in Figure 2, the main power quality indices, namely THDI, THDV and PF, would be given as [16]:

$$THDI = \frac{\sqrt{\sum_{h \geq 2} I_h^2}}{I_1} \cdot 100 \quad (9)$$

$$THDV = \frac{\sqrt{\sum_{h \geq 2} V_h^2}}{V_1} \cdot 100 \quad (10)$$

$$PF = \frac{P}{S} = \frac{\sum_h V_{Lh} I_h Cos(\theta_h)}{\sqrt{\sum_h V_{Lh}^2}\sqrt{\sum_h I_h^2}} \quad (11)$$

where V_h and V_{Lh} are the rms values of hth harmonic line-to-neutral voltages measured at point of common coupling and the load bus, and θ_h denotes the difference between hth harmonic load bus voltage ($\underline{V}_{Lh}$) and line current ($\underline{I}_h$).

It can be mentioned from (4), (9) and (11) that THDI or PF may not be used as a measure for the determination of cable's current carrying capability under nonsinusoidal currents. In other words, maximization of both indices does not mean maximization of the cable's current carrying capability.

IV. Formulations of the Studied Optimal Filter Design Problems

The problem formulations of the proposed optimal filter design approach based on the maximization of HDF and two traditional design approaches based on PF maximization and THDI minimization are presented in this section. In addition, the optimization search method, which is employed to find the solution of three optimal design problem, is introduced finally.

A. The Proposed Approach

Regarding maximization of the current carrying capability of cables which are intended to supply nonlinear loads, optimal passive filter design problem could be written as follows:

Maximize HDF (X_M, X_F and R_F) (12)
subjected to:
90% ≤ PF (X_M, X_F and R_F)≤ 100% (13)
THDV (X_M, X_F and R_F)≤ 5% (14)
THDI (X_M, X_F and R_F)≤ 15% (15)

Equation (12) and (13)-(15) are the objective function and inequality constraints of the problem formulation, respectively.

B. The Traditional Approaches

As mentioned before, in the literature, maximization of PF and minimization of THDI have widely been considered as objectives for optimal design of the passive harmonic filters. Accordingly, the traditional optimal design problems can be given respectively, as follows:

Maximize PF (X_M, X_F and R_F) (16)
Minimize THDI (X_M, X_F and R_F) (17)

Both objectives are subjected to the same nonlinear constraints given in (13)-(15).

C. The Optimization Algorithm

Grid Search (GS) Method, which is one of the most reliable optimization methods [15], is used to solve above formulated three optimal design problems.

In GS Method, firstly, feasible boundaries of the filter parameters are determined and then the objective functions are evaluated for all feasible values of the filter parameters.

Consequentially, their values corresponding to the minimum or the maximum value of the considered objective functions complying with the given inequality constraints are selected as the optimal filter designs.

V. Case Study and Results

Fundamental frequency supply voltage and short-circuit power of the simulated three-phase balanced and nonsinusoidal system are set as 6350 V (line-to-line) and 720 MVA.

For the simulated system's single-phase equivalent circuit, the impedance parameters are R_S = 0.0048 Ω, X_S = 0.0556 Ω, R_{B1}= 0.00245 Ω, X_{B1}= 0.00260 Ω, X_C= 100.00 Ω, R_L= 4.00 Ω and X_L = 4.05 Ω. Voltage and current harmonic sources of the single-phase equivalent circuit are given in Table I. The cable placed in the system has ratings and properties as 6.35 kV, Trefoil formation, PVC insulated, Unarmoured, single core copper wire 240 mm^2 cross sectional area. The rated current of the cable is 640 amperes [20].

Table I
Voltage and Current Harmonic Sources for the Single-Phase Equivalent Circuit

h	$\bar{V}_{Sh}(\%\bar{V}_{S1})$	$\bar{I}_{Lh}(A)$
5	$1.00\angle 0^\circ$	$84.00\angle -5\cdot 45^\circ$
7		$42.00\angle -7\cdot 45^\circ$
11		$24.50\angle -11\cdot 45^\circ$
13		$24.50\angle -13\cdot 45^\circ$
17, 19, 23, 25		$10.50\angle -h\cdot 45^\circ$
29, 31, 35, 37		$7.00\angle -h\cdot 45^\circ$
41, 43, 47, 49		$5.25\angle -h\cdot 45^\circ$

Under above detailed system conditions, the three-phase active ($P_{3\phi}$=3P), apparent ($S_{3\phi}$=3S) powers and PF measured at the load terminal are 4.900 MW, 7.098 MVA and 0.6903. THDV and THDI values measured at the PCC are 10.93% and 32.85%, respectively. The HDF value of the cable is 0.7951. Thus, the maximum three-phase power, which can be delivered by the cable, is found as: S_{Max}=3*3654*640*0.7951=5.578 MVA. Therefore, it can be seen that the cable is not able to supply the load side in the system even if the fundamental harmonic rms value of the line current is 613.83 amperes well below the cable's rated current.

On the other side, the THDV and THDI values are not complying with the IEEE Standard 519-2014, as they should be below or equal 5.00% and 15.00%, respectively. Accordingly, a passive filter should be employed for both power factor correction and harmonic mitigation in the simulated system.

For the system with the optimal *C*-type filter designed according to the three approaches, simulation results are given in Table II.

TABLE II
THE RESULTS OBTAINED FOR THE SYSTEM WITH THE FILTERS BASED ON THREE DESIGN APPROACHES

Parameters	PF Maximization	THDI Minimization	HDF Maximization
X_M (Ω)	6.220	5.860	5.860
X_F (Ω)	0.264	0.249	0.257
R_F (Ω)	11.391	11.220	6.783
THDV (%)	2.90	2.86	2.20
THDI (%)	14.95	14.07	14.83
PF	0.9268	0.9022	0.9015
HDF	0.956	0.960	0.964
S_{Max} (MW)	6.744	6.777	6.804

This table shows that the proposed approach provides higher S_{Max} value when compared to other two optimal design approaches. It can also be figured out from the results that THDI values obtained by the proposed and the PF maximization based approaches are very close to each other, and the proposed one has the lowest THDV value as compared with other two approaches. On the other hand, the proposed and the THDI minimization based approaches have the same reactive power compensation due to the fact that they result in almost the same PF improvement.

VI. CONCLUSION

In this paper, an approach for effective utilization of power cables under nonsinusoidal conditions is proposed. Maximization of harmonic derating factor for the power cable is taken into account as an objective function of the optimal passive filter design problem. Regarding IEEE Standard 519-2014, the total harmonic distortions of the voltage and current measured at the point of common coupling are handled as the main constraints of the proposed approach. Besides, preserving load's true power factor at its adequate range is achieved.

The simulation results figured out that the proposed approach provides higher current carrying capability of the cables under nonsinusoidal conditions compared to the conventional approaches, while maintaining the current and voltage harmonic limitations of the IEEE Standard 519-2014.

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