Electrical Power and Energy Systems 71 (2015) 344–350

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Effective utilization of cables and transformers using passive filters for non-linear loads

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ARTICLE INFO

Article history:
Received 22 February 2014
Received in revised form 2 February 2015
Accepted 20 February 2015
Available online 7 April 2015

Keywords:
Harmonic distortion
Non-sinusoidal conditions
C-type filters
Optimal design
Cable derating
Transformer derating

ABSTRACT

In the literature, it is well known that transformers and cables have excessive losses or overheating under non-sinusoidal current conditions. Accordingly, they have reduced current carrying capabilities (or loading capabilities) for that kind of conditions. This paper aims to employ passive filters for the effective utilization of the cables and transformers in the non-sinusoidal systems. Consequently, an optimal passive filter design approach is provided to maximize the power factor expression, which takes into account frequency-dependent line losses, under non-sinusoidal background voltage and line current conditions. The individual and total harmonic distortion limits placed in IEEE standard 519 are taken into account as constraints for the proposed approach. Besides, keeping the load's displacement power factor at an adequate range is desired by the proposed approach. The proposed approach and the traditional optimal passive filter design approach, which aims to maximize the classical power factor expression, are comparatively evaluated for an industrial power system with a group of linear and non-linear loads, overhead transmission lines, cables and a transformer. Numerical results show that the proposed one has a considerable advantage in the improvement of the total supply line loss and the transformer's loading capability under non-sinusoidal conditions when compared to the traditional one. On the other hand, for the simulated system cases, both approaches lead to almost the same current carrying capability value of the cables.

Introduction

Power electronic devices such as adjustable speed drives, power rectifiers and inverters, are widely employed to control large power electrical loads in present day's power systems [1]. The loads controlled via power electronic devices, generally called as non-linear loads, draw non-sinusoidal or harmonically contaminated currents from the utility. Since non-sinusoidal currents cause non-sinusoidal voltage drops on the lines, these loads also result in distorted point of common coupling (PCC) voltages. Accordingly, in the literature, great interests have been focused on the adverse effects of the harmonics on the power distribution equipment such as cables [2–7] and transformers [8–13]. It is seen from these studies that due to the fact that the resistances of the cables and the transformer windings increase with the frequency, they have excessive losses even if the root-mean-square (rms) value of the harmonically distorted load currents are lower than their sinusoidal rated currents. Therefore, current harmonics cause the reduction of their useful life [14]. To prevent cables and transformers from these adverse effects of the harmonics, they should be derated under non-sinusoidal current conditions [6,13]. The needed derating factor (maximum permissible current carrying or loading capability) can be calculated as the ratio between the non-sinusoidal load current's rms value, which leads to the rated loss of the equipment (transformer or cable), and the equipment's rated sinusoidal current.

Power factor is conventionally used as an indicator of how effectively are utilized the power transmission and distribution equipment in the power systems [15,16]. Accordingly, passive filters are widely designed to maximize the classical power factor expression in the literature [17–20]. However, it can clearly be seen from [21] that maximization of classical power factor definition, which is calculated as the ratio between active and classic apparent power, does not achieve the minimum loss case of a power system having transmission and distribution lines with frequency-dependent resistances.

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http://dx.doi.org/10.1016/j.ijepes.2015.02.036

Nomenclature

$\underline{V}_{Sh}, \underline{I}'_{Lh}$	phasor values of the *hth* harmonic voltage and *hth* harmonic current sources
$\underline{V}_h, \underline{I}_h$	*hth* harmonic voltage at the point of common coupling (PCC) and *hth* harmonic line current phasors
$\underline{V}'_{Lh}$	*hth* harmonic load voltage phasor referred to the primary side of transformer
φ_h	phase angle difference between *hth* harmonic load voltage, which is referred to the primary side of the transformer, and *hth* harmonic line current
DPF	displacement power factor
PF	classical power factor
THDI	current total harmonic distortion
THDV	voltage total harmonic distortion
P_1	fundamental harmonic active power
S_1	fundamental harmonic apparent power
P	total active power
S	classical apparent power
FHL	harmonic loss factor
$P_{LL\text{-}R}$	transformer's winding rated loss
$P_{EC\text{-}R}$	transformer's winding eddy-current rated loss
DF_{TR}	loading capability of a dry-type transformer supplying a non-linear load
DF_{CB}	current carrying (or loading) capability of a cable supplying a non-linear load
ΔP_{Total}	total transmission and distribution line loss
PF_e, S_e	power factor and apparent power, which are calculated by considering the frequency dependency of the supply line resistance

In this paper, optimal design of passive filters for effective utilization of transformers and cables operating under harmonically contaminated voltage and current cases is proposed, while taking into account the frequency-dependent nature of their power losses. Accordingly, maximization of the power factor definition [21], which considers frequency-dependent loss of the supply lines, is regarded as the objective function of the proposed optimal filter design approach. It also has the constraints as the individual and total harmonic distortion limits and the displacement power factor (fundamental harmonic power factor) recommendation included in IEEE Standard 519–1992 [22]. The proposed approach can be applied to any kind of passive filters such as single-tuned and high pass filters [20]. However, the *C*-type filter is selected to demonstrate the proposed approach since it has good filtering performance, damping resonance capability and lower fundamental frequency loss when compared to other types of the filters [20].

This paper is organized as follows, on which the present context forms Section "Introduction" as an introduction to the work. Section "Modelling of the studied system" is devoted to the detailed harmonic-domain modelling of the system with a power transformer and cable under polluted voltages and currents. Section "Problem formulations of traditional and proposed optimal design approaches" interprets the problem formulations of the proposed approach based on maximization of the power factor defined in [21] and the traditional design approach based on maximization of the classic power factor definition. Simulation results obtained for both approaches are discussed in Section "Simulation results". The conclusion is presented in Section "Conclusion".

Modelling of the studied system

In this paper, optimal passive filter design is studied for the typical industrial power system, which is primarily taken from [22] and considered in many previous works [17–19,23–25]. Its single-line diagram is given in Fig. 1. It has a consumer with three-phase linear and non-linear loads, the consumer's transformer and power cable, which carry energy from PCC to the loads and a *C*-type filter connected to load bus. It should be mentioned that some of the linear loads are compensated with an individual capacitor.

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 [26–28], which are referred to the primary side of the transformer, where h is the harmonic number. The referred *h*th harmonic impedance of the individual compensation capacitor, which is pre-installed for the linear loads in the consumer side, is denoted by $-jX'_{Ci}/h$.

Utility side can be modelled as Thevenin equivalent voltage source $(\underline{V}_{Sh})$ and Thevenin equivalent impedance $(\underline{Z}_{Sh})$ for each harmonic order. Regarding the skin effect [21]; the *h*th harmonic resistance (R_{Sh}) of the supply line (Thevenin equivalent) impedance and the *h*th 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 resistances of the supply lines and cables, respectively. In addition, the *h*th harmonic inductive reactances of the supply lines and cables can be expressed as $X_{Sh} = hX_S$ and $X_{CBh} = hX_{CB}$, respectively. Note that capacitance of the short overhead lines and all cables can be neglected for the harmonic analysis [28].

With respect to the milestone studies on the harmonic modelling and simulation [26–28], the consumer's transformer can practically be modelled using its 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 *h*th 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}) [9,10]:

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

Fig. 3 shows that single-phase circuit representation of the *C*-type filter [23]. It consists of the main capacitor (X_{CF1}) in series with a parallel connection of series inductor (X_{LF})-capacitor (X_{CF2}) branch and damping resistor (R_F). The main capacitor provides the fundamental harmonic capacitive reactive power to attain desired *DPF* value. In the *C*-type filter, series inductor-capacitor branch is tuned to fundamental harmonic for avoiding its fundamental harmonic losses. This case means that fundamental frequency reactance values of the series connected inductor and capacitor are equal to each other $(X_{CF2} = X_{LF} = X_F)$. The value of the damping resistor is an important parameter for provision of the desired quality factor, which is a measure of the sharpness of the tuning frequency.

The *C*-type filter's *h*th harmonic impedance, which is referred to the primary side of the consumer's transformer, can be found as;