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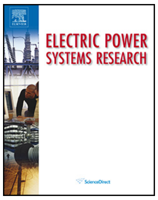

Comparative evaluation of common passive filter types regarding maximization of transformer's loading capability under non-sinusoidal conditions

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ABSTRACT

This study aims to comparatively evaluate the widely known five passive harmonic filters as single-tuned, double-tuned, triple-tuned, damped-double tuned and C-type ones by regarding their contribution on the loading capability improvement of the transformers under non-sinusoidal conditions. For the comparative evaluation, the studied filter types are optimally designed to minimize the harmonic loss factor index, which is defined as a tool to determine the transformer's permissible loading capability 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 and displacement power factor are considered as constraints of the studied optimal filter design problems. Whales optimization (WO) algorithm, which has recently been introduced in the literature, is used to find the optimal filter solutions. To show the validity of the obtained optimal filter designs, the results are also provided via Particle Swarm Optimization (PSO) algorithm. The simulation results show that the studied filters can be ranked from the best to worst as triple-tuned, damped double-tuned, double-tuned, C-type and single-tuned ones in terms of their performance on the transformer's loading capability improvement. It is also seen from the simulations that the results of WO and PSO algorithms are very close to each other, and WO algorithm achieves optimal design solutions with considerably lower iteration numbers and run times.

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, draw non-sinusoidal or harmonically contaminated currents from the system. Due to the fact that non-sinusoidal currents cause non-sinusoidal voltage drops on the lines, these loads also result in distorted point of common coupling (PCC) voltages. 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 and active filters [2].

Active filters are divided into series and shunt types, and they are power electronic devices controlled as voltage harmonic and current harmonic sources for mitigation of load voltage and line current harmonic distortions, respectively [3]. They have superior performance on harmonic mitigation and reactive power compensation when compared to passive filters. However, for the same power level, they have extremely higher costs with respect to passive filters. Thus, passive ones are widely employed for harmonic mitigation and power factor improvement.

Passive filters, which are constructed with resistances, inductors and capacitors, are mainly classified as series and parallel passive filters with respect to their connection into the system [4]. Series passive filters behave as a high series impedance to block the respected harmonic current flow between source and load sides for their tuning harmonic frequencies. Shunt passive filters provide a shunt low impedance to turn the harmonic currents, which have frequencies around their tuning frequencies, from phase line to neutral point. Due to the fact that shunt passive filters achieve not only harmonic mitigation but also fundamental harmonic reactive power compensation, they are much preferred than series ones

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Nomenclature

DPF	Displacement power factor measured at PCC
F_{HL}	Harmonic loss factor
F_{V}, P_{V}, U_{V}	Utilization percentage, present value and consumption charge rate of the filters
FC, IC, OC	Total, investment and operational costs of the filter
FS	Impedance-frequency response or resonance damping capability index
I_{max}	RMS current capability of a dry-type transformer supplying a non-linear load
P_1, S_1	Fundamental harmonic active and apparent powers measured at PCC
$P_{LL\text{-}R}$	Transformer's winding rated loss
$P_{EC\text{-}R}$	Transformer's winding eddy-current rated loss
$Q_{\Sigma \mathrm{C}}$, $Q_{\Sigma \mathrm{L}}$	The total volt-ampere ratings of the capacitors and inductors, which are included in the filters
S_{max}	Loading capability of a dry-type transformer supplying a non-linear load
$THDI$, $THDV$	Current and voltage total harmonic distortions measured at PCC
U_C and U_X	The unit costs of the capacitor and inductor
$\underline{V}_h$, $\underline{I}_h$	Voltage and current phasors at point of common coupling (PCC) for hth harmonic
V_h, I_h	Voltage and current rms values at PCC for hth harmonic
$\underline{V}_{Lh}$, V_{Lh}	Phasor and rms values of the load voltage referred to the primary side of the transformer
φ_h	Phase angle difference between hth harmonic PCC voltage and line current
ΔP_S, ΔP_{Tr}, ΔP_F	The losses of the supply line, transformer and filter

[2]. On the other side, shunt passive filters have several types as single-tuned, double-tuned, triple-tuned, damped double-tuned, first-order high-pass, second-order high-pass and C-type filters according to their frequency response [4].

Since current total harmonic distortion (*THDI*), voltage total harmonic distortion (*THDV*), power factor (*PF*), the filter's loss ($\Delta \mathrm{P_F}$) and the filter's cost (*FC*) can be affected in an opposite manner to the passive filters, design of passive filters are studied as optimization problem in the literature. Accordingly, maximization of *PF* and minimization of *THDV*, *THDI*, $\Delta \mathrm{P_F}$ and *FC* are traditionally regarded as objectives in the formulation of the optimal passive filter design problem [5–9]. In the literature, the passive filters has recently been employed for the distributed generation (DG) hosting capacity improvement of the systems with the non-linear loads and the DG units based on the power electronic devices [10].

The traditional harmonic distortion measurement indices, *THDI* and *THDV*, are only a measure of current and voltage wave shape distortion, and they do not take into account frequencies of current and voltage harmonics [11]. Due to this, *THDI* index is limited to express both harmonic related winding losses and non-linear loading capability of transformers, which depend on not only magnitudes but also frequencies of the load current harmonics. As a result, IEEE standard C57.110 [12] presents the harmonic loss factor (F_{HL}) index of the non-sinusoidal load current to determine the loading capability of transformers under non-sinusoidal conditions. Accordingly, in Refs. [13,14], authors employed single-tuned and C-type passive filter designs to maximize the loading capacity of a transformer, which is dedicated to supply non-linear loads in the typical industrial power system with distorted background voltage. Objective function of both optimal designs is to minimize F_{HL}, and by regarding IEEE standard 519 [15], their constraints are chosen as total and individual harmonic distortion limitations of the PCC voltages and line current and desired displacement power factor interval.

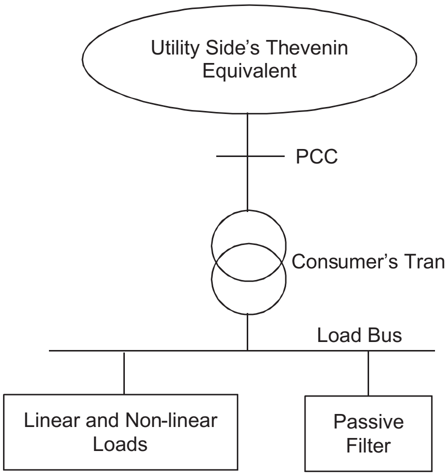

Fig. 1. Single line diagram of the typical industrial power system.

The main goal of this paper is to comparatively evaluate the widely known passive harmonic filters as single-tuned, double-tuned, triple-tuned, damped double-tuned and C-type ones by regarding their contribution on the loading capability improvement 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 [5,6,13,14]. It is represented with the harmonic models of the system equipment widely considered in the literature [16–19]. Optimal passive filter design problem is solved by using two meta-heuristic techniques as Wales Optimization (WO) algorithm, which has recently been introduced in Ref. [20], and Particle Swarm Optimization (PSO) algorithm, which is successfully employed for solution of the optimal passive filter design problem in the several studies [5,8,21].

2. Harmonic modelling of the 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 carries energy from PCC to the consumer, and a passive filter connected to load bus.

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 practical solution is valid since the studied system is balanced. In the same 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 [16–18], 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 in the system since the total harmonic distortion (*THDV*) level measured at the load bus is less than 10% [17]. Utility side is modelled as Thevenin equivalent voltage source ($\underline{V}_{Sh}$) and Thevenin equivalent impedance ($\underline{Z}_{Sh} = R_S + jhX_S$) for each harmonic order.

For the studied system, by considering the milestone studies on the harmonic modelling and simulation [16–18], the consumer's