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Optimal resonance-free third-order high-pass filters based on minimization of the total cost of the filters using Crow Search Algorithm

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ABSTRACT

The most common damped filters (DFs) are the second-order, third-order, *C*-type, and double-tuned filters. Other DFs such as the first-order and band-pass filters exist, but their high operating losses considerably diminish their usage. In this paper, firstly, for the third-order damped filter with equal and unequal capacitors, the relations among their circuit parameters are derived. Secondly, the optimal design problem of the two third-order high-pass filters is formulated by regarding these expressions to minimize the filter cost taking into account both the investment and operating expenses. The total and individual harmonic distortion indices, power factor and the harmonic voltage amplification ratios which measure the filter's resonance damping capability, are considered as constraints. A recent metaheuristic optimization technique based on the intelligent behavior of crows, known as the Crow Search Algorithm (CSA), is employed for the solution of the formulated design problem. Further, a comparative analysis of the two designs of the third-order high-pass filters and a third-order *C*-type filter is presented. The results reveal that all the proposed filters guarantee no electrical resonance hazards while maintaining the allowable limits for the various performance indices of the system, load, and filter. Besides, the comparative analysis validates that the *C*-type filter provides higher power factor, system efficiency and transmission loss improvement than the other two filters, and that the proposed filters achieve almost the same voltage and current harmonic mitigation levels. The solution of the cost minimization problem reveals that the *C*-type filter and the third-order high-pass filter with equal capacitors have the worst and best resonance damping capabilities respectively, under the worst case conditions. Additionally, the filters with the lowest and highest cost are found as the third-order filter with unequal capacitors and the *C*-type one, respectively. Besides, the CSA is compared to the genetic algorithm (GA), and particle swarm optimization (PSO) techniques and the results show the fast convergence capability and the effectiveness of the proposed algorithm in solving the problem of optimal design of third-order resonance-free passive filters in distribution networks.

1. Introduction

Harmonic distortion is one of the main power quality problems for power systems, particularly with the advance of power electronic equipment and nonlinear loads that worsen the quality of power. Recently, other developments in power systems have led to new challenges in the quality of the power domain, such as integration of large-scale renewable energy based generation technologies, and the expansion of interconnected power grids [1–6].

Among the numerous solutions and power conditioning devices that improve the quality of power and mitigate harmonics; passive filtering is still widely used for voltage support, reactive power compensation, and harmonic mitigation in transmission and distribution systems due to simplicity, low cost, easy surveillance and maintenance, and high reliability [7]. On the other hand, tuned passive filters suffer from various drawbacks such as parameter variations that may occur due to frequency deviation, manufacture

Abbreviations: CSA, Crow Search Algorithm; DF, damped filter; GA, genetic algorithm; OF, objective function; PSO, particle swarm optimization.

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Nomenclature

AP	Awareness probability
DPF	Displacement power factor
E_{Sn}	The harmonic system background voltage at harmonic order n
FC	Total cost of the filter
fl	Flight length
F_{PL}	Power losses associated with the filter
FS	Impedance-frequency response index
F_V	Filter utilization percentage
h	Tuning order of the filter
HDI_n	Individual harmonic distortion of the line current at harmonic order n in percent
HDI_{std}	The IEEE standard 519's limit of the HDI_n in percent
HDV	Individual harmonic distortion of the load voltage in percent
HDV_n	Individual harmonic distortion of the load voltage at harmonic order n in percent
HDV_{std}	The IEEE standard 519's limit of the HDV_n in percent
HMC	Harmonic mitigation capability of the filters in percent
$HVAR$	Harmonic voltage amplification ratio
$HVAR_{ref}$	Reference (limit) value of $HVAR$
$HVAR_{worst}$	$HVAR$ value for the worst case scenario
i	Interest rate
I_C	Rms current of the main capacitor (C_1) of the filters
IC	Investment cost of the filter
$I_{NL}(\omega)$	Harmonic nonlinear load current at the angular frequency (ω)
I_{rated}	Rated current of the main capacitor (C_1) of the filters
I_{Sn}	The nth harmonic line current
k	Lifetime of filter in years
OC	Operating cost of the filters
n	Harmonic number
PF	Power factor in percent
P_V	Present value
Q_{C1}, Q_{C2}	Reactive power drawn by the main capacitor (C_1) and auxiliary capacitor (C_2) of the filters
Q_{rated}	Rated reactive power of the main capacitor (C_1) of the filter
Q_x	Reactive power drawn by the inductor (L) of the filters
$R_F(\omega)$	The filter's equivalent resistance at the angular frequency (ω)
R_{Fn}	The nth harmonic resistance of the nth harmonic filter impedance Z_{Fn}
R_{Sn}	The nth harmonic resistance of the nth harmonic Thevenin equivalent impedance of the source side Z_{Sn}
t	Iteration number
t_{max}	Maximum number of iterations
$THDI$	Total harmonic distortion of the line current in percent
$THDV$	Total harmonic distortion of the load voltage in percent
TP_L	Transmission power loss
U_C, U_X	Unit costs of the capacitors and inductors of the filters, respectively
U_V	Consumption charge rate
V	Nominal voltage of the system
V_C	Rms voltage of the main capacitor (C_1) of the filters
V_{Ln}	The nth harmonic load voltage
V_{peak}	Peak voltage of the main capacitor (C_1) of the filters
V_{rated}	Rated voltage of the main capacitor (C_1) of the filters
$X_F(\omega)$	The filter's equivalent reactance at the angular frequency (ω)
X_{Fn}	The nth harmonic reactance of the nth harmonic filter impedance Z_{Fn}
X_{Sn}	The nth harmonic reactance of the nth harmonic Thevenin equivalent impedance of the source side Z_{Sn}
$Z_F(\omega)$	The filter equivalent impedance at the angular frequency (ω)
$Z_L(\omega)$	The linear load impedance at the angular frequency (ω)
$Z_{FL}(\omega)$	The parallel equivalent impedance of $Z_F(\omega)$ and $Z_L(\omega)$ at the angular frequency (ω)
Z_n	The nth harmonic equivalent impedance seen from the harmonic current source side
$Z_S(\omega)$	The system Thevenin equivalent impedance at the angular frequency (ω)
α, β, γ	Collective variables used for expressing $R_F(\omega)$ and $X_F(\omega)$
η_T	Transmission efficiency in percent
φ_n	The harmonic phase difference between the nth harmonic load voltage and line current
ω_h	Angular frequency at the tuning harmonic order (h) of the filter

tolerance, and temperature change. Besides, the filtering performance is affected by the source resistance which may vary and hence leads to resonance occurrence between the filter and system [3,8–10].

Passive filters were firstly installed in the 1940s [9]. In its broadest scene, they are classified based on the method of connection into the series and shunt filters. Series filters present a high-impedance series path to block harmonics at the tuning frequency, while shunt filters present a low-impedance shunt path to divert harmonics at the tuning frequency. Shunt filters are still more employed for harmonics mitigation than the series filters because of the significant fundamental power loss and voltage drop of series filters, as well as their high fundamental voltage-ampere (VA) rating. Moreover, shunt filters are capable of supporting voltage and compensating reactive power at the fundamental frequency [3,11,12].

According to the nonlinear loads being considered, series filters are more suitable for voltage-source nonlinear loads or AC drives [13], while shunt filters are more suitable for current-source nonlinear loads or DC drives [14].

Further, shunt filters are classified based on their function, into tuned and damped filters. Tuned filters are filters that are adjusted to mitigate harmonics by providing a low impedance path at one, two, or even three tuning harmonic frequencies, known as single-tuned, double-tuned, and triple-tuned (less common) filters, respectively. Single-tuned filters are common in distribution systems and industrial applications, while the double-tuned and the triple-tuned filters are common in high-voltage applications and high-voltage direct current (HVDC) transmission systems [3,11]. On the other hand, damped filters such as the first-order, second-order, third-order, *C*-type, damped double-tuned, and bandpass filters, are high-pass filters (HPFs) that provide a low impedance path to a broad range of harmonics [3,15]. They are widely used in transmission systems, HVDC links, and recently in distribution and industrial systems [16,17]. Compared to the tuned filters, they are less sensitive to variations that may occur due to frequency deviation, manufacture tolerance, and temperature change. Also, they can dampen the harmonic amplification which may occur by the