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The engineering design and optimization of main circuit for hybrid active power filter

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A B S T R A C T

This paper analyzes the alternative of a hybrid active power filter (HAPF) connected to the medium-voltage (10 kV) distribution network to enhance the power quality. It proposes a multi-objective optimization algorithm based on improved particle swarm optimization (PSO) to design and optimize the main circuit of HAPF. On the basis of theoretical analysis, it removes engineering experience and redundant constraints from the optimization algorithm, and establishes a unified description of performance for HAPF. To avoid premature of PSO algorithm, an adaptive inertial weight based on sigmoid function is employed to improve the diversity of the solution space. The simulation and experimental results show that the proposed design and optimization of main circuit for HAPF is correct and effective.

1. Introduction

Due to the increasing application of nonlinear loads, power grid is now heavily polluted by harmonics [1,2]. There are three solutions—Passive Power Filter (PPF), Active Power Filter (APF) and Hybrid Active Power Filter (HAPF) to resolve the harmonic pollution problem in power grid [3–5]. Although PPF is simple and less expensive, its filtering characteristics are heavily dependent on parameters of power grid, therefore it may be easily detuned and incur resonance. APF can overcome some defects of PPF, and it is much more effective in filtering dynamic harmonics. However, the cost of APF is much higher, and the extensive application of pure high-power APF is not feasible. By making a good tradeoff between filtering performance and the cost of investment, HAPF is a good combination of PPF and APF [6]. In this paper, among various topologies of HAPF, the one with injection circuit and resonance circuit is presented, which is especially suitable for the application of harmonic elimination in high-voltage and high-power field.

For a given topology and control strategy, the proper combination of main circuit parameters is essential to assure the performance and reduce the cost of HAPF [7–9]. Recently, in the literature, there are some studies about the optimal design of HAPF main circuit, but the designs presented in those studies suffer from many constraints of engineering experience, which is comparatively rough, unnecessarily costly for some time, and of losing optimization diversity [10–12].

In order to increase the variety of the optimal solution for the design of main circuit, based on improved Particle Swarm Optimization (PSO), a novel multi-objective optimization algorithm for the design of main circuit of HAPF is proposed. In this optimization algorithm, a unified performance description of HAPF is established, and the objective function and suitable constraints based on theoretical analysis are summarized. Since an adaptive inertial weight based on sigmoid function and nonlinear time-varying acceleration parameters are employed to PSO algorithm, the optimal solution of HAPF main circuit are more various. Furthermore, with the proposed method, the influence of engineering experience and redundant constraints could be got rid of, and the convergence rate and diversity of multi-objective optimization algorithm are improved.

2. Topology and theory of HAPF main circuits

The topology of main circuit of HAPF, which consists of injection circuit and the active part, is shown in Fig. 1. Where e_s is the voltage source of power grid, L_s is the equivalent inductor of lines in power supply side, T_f is the coupling transformer with ratio $m = 1$, C_f and L_f are the capacitor and inductor of APF output filter, respectively. The injection circuit is composed of C_{inj}, R, C_1 and L_1, and C_{inj} is injection capacitor, C_1, L_1 are capacitor and inductor of resonance circuit, respectively, R is the equivalent resistor of L_1. Capacitor C_{inj} is employed to share the most part of fundamental voltage, meanwhile, it provides low impedance path for harmonic currents. The C_1 and L_1 of resonance circuit tune near fundamental frequency, and this greatly decreases the power requirement of

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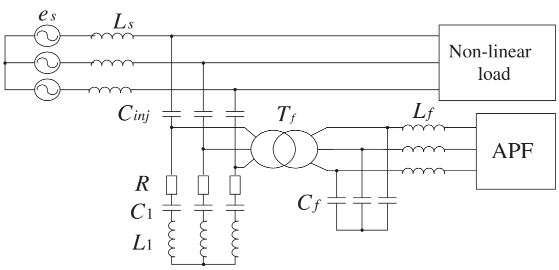

Fig. 1. The main circuit of HAPF.

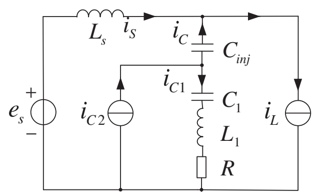

Fig. 2. The single-phase equivalent circuit of HAPF.

APF; At fundamental frequency, the impedance of resonance circuit is determined by R, C_1 and L_1. The APF, realizing the function of restraining harmonics, consists of the output filter, coupling transformer and voltage source inverter. The output current of the active part flows into power grid through injection circuit, and the output filter is utilized to filter out the switching harmonics caused by power electronic devices.

To briefly describe the operation principle of HAPF, a single-phase equivalent circuit of HAPF is shown in Fig. 2.

The approximate expression of single phase load current is written as

$$i_L = \sum_{n=1}^{N} \sqrt{2} I_L^n \cos\left(n\omega_1 t + \theta_L^n\right) \tag{1}$$

where I_L^n is the Root Mean Square (RMS) value of nth harmonic current of load current, ω_1 is the angular frequency of fundamental current, θ_L^n is the initial phase of nth harmonic current of load, N is the highest order of harmonic concerned in load current.

According to the single-phase equivalent circuit of HAPF, the part of nth harmonic component of current of active part is

$$i_C^n = i_{C2}^n - i_{C1}^n \tag{2}$$
$$i_{Sh}^n = i_L^n - i_C^n \tag{3}$$

where $i_L^n,\ i_C^n,\ i_{Sh}^n$ stand for nth harmonic component of load current i_L, compensation current i_C, and grid current i_S, respectively, in which $i_L^n = I_L^n \angle \theta_L^n, i_C^n = I_C^n \angle \theta_C^n, i_{Sh}^n = I_{Sh}^n \angle \theta_{Sh}^n,\ I_C^n,\ I_{Sh}^n$ are the RMS values of nth harmonic component of HAPF compensation current and grid current, $\theta_C^n,\ \theta_{Sh}^n$ are the initial phases of nth harmonic component.

Suppose $X^n(\omega)$ is the impedance of passive component for nth harmonic, and $X^n(R_R)$ is the impedance of resonance circuit, so $X^n(R_R) = X^n(C_1) + X^n(L_1)_R$, then e_s^n, the part of n^{th} harmonic component of grid voltage is

$$e_s^n = i_{Sh}^n X^n(L_s) - i_C^n X^n(C_{inj}) + i_{C1}^n X^n(R_R) \tag{4}$$

If APF is not in operation, nth harmonic component of grid current i_{Sh}^n is

$$i_{sh}^n = \frac{e_s^n}{X^n(L_s) + X^n(C_{inj}) + X^n(R_R)} + i_L^n G_L^n \tag{5}$$

where G_L^n is

$$G_L^n = \frac{X^n(C_{inj}) + X^n(R_R)}{X^n(L_s) + X^n(C_{inj}) + X^n(R_R)} \tag{6}$$

If APF is in operation, and the control strategy for HAPF is defined as

$$i_{C2}^{n*} = i_L^n \tag{7}$$

where i_{C2}^{n*} is nth harmonic component of reference current for APF.

If i_C^n, nth harmonic component of output current of APF is controlled to track i_{C2}^{n*} in HAPF system, according to Eqs. (1)–(7), nth harmonic component of grid current i_{Sh}^n is expressed as

$$i_{sh}^n = \frac{e_s^n + i_L^n X^n(C_{inj})}{X^n(L_s) + X^n(C_{inj}) + X^n(R_R)} \tag{8}$$

Usually, the harmonic voltage of power grid is very small, but it may cause parallel resonance. In the engineering design of HAPF, it should consider the constraint to avoid parallel resonance.

If

$$G_S^n = \frac{X^n(C_{inj})}{X^n(L_s) + X^n(C_{inj}) + X^n(R_R)} \tag{9}$$

Apparently, $|G_s^n(\omega)|$ should be very small, so that n^{th} harmonic component of source current can be restrained in a lower range. If $|X^n(L_1) + X^n(C_1)|$ is big enough, and the impedance $X^n(L_s)$ of power line is small enough, Eq. (9) can be simplified as

$$|G_S^n| = \left| \frac{X^n(C_{inj})}{X^n(C_{inj}) + X^n(R_R)} \right| \tag{10}$$

Suppose C_1, L_1 and C_{inj} cause serial resonance at kth harmonic component, that is $|X^k(L_1) + X^k(C_{inj}) + X^k(C_1)| = 0$. According to Eq. (8), kth harmonic component may be magnified by HAPF, so HAPF should not compensate the kth harmonic current to avoid harmonic amplification.

According to Eqs. (1)–(10), The nth harmonic current i_{Sh}^n, when compensated by HAPF, can be described as

$$i_{Sh}^n = i_L^n \min\left\{ |G_L^n(\omega)|, |G_s^n(\omega)| \right\} \tag{11}$$

3. Description of optimal design of HAPF main circuit

The optimization objectives of HAPF main circuit include two aspects—the best performance and the lowest cost. The main circuit of HAPF includes the active part and the injection circuit, therefore, the performance and cost of injection circuit and active part will be separately discussed here.

3.1. The objective for the optimization

3.1.1. Cost minimization

The investment cost of HAPF System, J_{cost}, includes costs of the active part J_{apf} and the injection circuit J_{inj}, that is

$$J_{\text{cost}} = J_{apf} + J_{inj} \tag{12}$$

The cost of components is mainly determined by their power ratings. The rating of C_{inj}, C_1 and L_1, are denoted as S_{Cinj}, S_{C1} and S_{L1}, respectively.

According to Fig. 2, the rating S_{Cinj} of injection capacitor C_{inj} is

$$S_{Cinj} = \frac{3}{\omega C_{inj}} \sum_{n=1}^{N} \frac{(I_C^n)^2}{n} \tag{13}$$

where I_C^n is the RMS value of nth harmonic component of output current in HAPF system.