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An impedance-match design scheme for inductively active power filter in distribution networks

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ABSTRACT

This article proposes an improved inductively active power filter (IAPF) to compensate the wide-bandwidth harmonics from nonlinear loads and eliminate the switching harmonics' adverse effect for its own inverter. At first, the topology that consists of an inductively filtering converter transformer (IFCT) and a shunt active power filter (SAPF) is proposed. The system equivalent circuit, including fundamental and harmonic impedances of IFCT and SAPF, is established to reveal the filtering mechanism. Besides, the mathematical model, control strategy and detailed output impedance of SAPF are described, respectively. Further, according to the equivalent circuit, comprehensive influences of IFCT equivalent impedance and SAPF out impedance on system compensation accuracy, perturbation rejection ability and stability are theoretically analyzed, the impedance-match operation constraints between two impedances are revealed. By proper IFCT design, a simple but practical method to reduce the interaction between IFCT and SAPF is proposed. Comparative simulation cases in 10 kV distribution networks and the proper experiment in 380 V condition are performed. The corresponding results validate the effectiveness and correctness of the proposed IAPF.

1. Introduction

The rapidly increasing application of nonlinear loads causes significant harmonics problem in distribution networks. Shunt active power filter (SAPF) has been considered one of the favored methods for harmonic compensation [1–5]. Usually, harmonics caused by nonlinear loads are compensated by SAPF locally or centrally, which means SAPF is installed at load-side or grid-side. However, neither centralized nor local SAPF can prevent harmonics from flowing into the converter transformer which is generally used to isolate dc supply systems from ac distribution networks. Harmonic leakage flux in converter transformer triggers additional iron and copper losses, vibration and temperature rise, etc.

In recent years, an inductive power filtering (IPF) method based on the balance of transformer's harmonic magnetic potential is presented [6]. The IPF method introduces a filtering winding of the converter transformer to balance out the harmonic magnetic flux at the load winding. Thus, the harmonic magnetic potential can be balanced between the load and the filtering winding, and the harmonic leakage flux in converter transformer decreases significantly. The original IPF method employs a set of single tuned filters to suppress harmonics, but these passive filters cannot reach resonance completely due to design error and material aging. Motivated by this, numerous improved methods are intensively studied. Literature [7] investigates a controllably inductive filtering method, in which the single tuned filter can be multi-tuned by means of virtual impedance. This controllably inductive filter with the feature of small capacity is suitable for specific harmonic compensation condition such as shipboard system, wind power system. Literature [8] presents an inductively active filtering method to improve the power quality for distribution networks firstly. The topology and control strategy are described comprehensively, but the compensation performance can be further improved due to its open-loop control scheme. Also, the inductively active filter fails to take switching harmonics suppression into consideration. The switching harmonics generated by inverter would inevitably induct to load winding and has an unfavorable effect on the sensitive load. In addition, by further investigating the filtering mechanism, it can be found that compensation performance and system stability is influenced by the impedance relationship between inductively filtering converter transformer (IFCT) and SAPF, which is not taken into consideration in detail in the existing design.

To address the above issues, this article proposes an inductively active power filter (IAPF) composed of SAPF and IFCT. SAPF suppresses switching harmonics and outputs wide-bandwidth (1st–49th)

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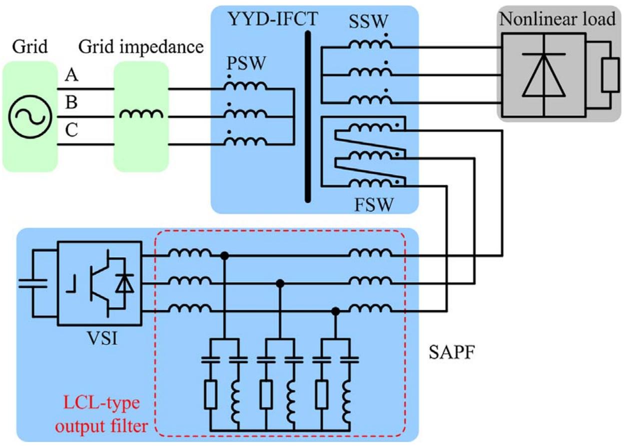

Fig. 1. The detailed wiring scheme of the proposed IAPF.

harmonics by the LCL-type output filter and the vector proportional integral (VPI)-based control method, respectively. With the aim of outputting 1st–49th harmonics to filtering winding of IFCT stably and accurately, the impedance-match design scheme between SAPF and IFCT is presented in detail. According to the constraints in this scheme, the proposed IAPF can obtain higher compensation accuracy, stronger output current perturbation rejection ability and larger stability margin.

The rest of the article is organized as follows. Section 2 analyzes the filtering mechanism on the basis of the system model. Section 3 describes SAPF mathematical model and the VPI control method. Section 4 proposes three constraints of impedance-match scheme between IFCT and SAPF. Comparative simulation cases in 10 kV distribution networks are given in Section 5. Section 6 presents experimental results with proper parameters. Finally, conclusions are given in Section 7.

2. System modeling and filtering mechanism

The detailed wiring scheme of the proposed IAPF is shown in Fig. 1. The proposed IAPF configures IFCT, SAPF consisted of voltage source inverter (VSI) and LCL-type output filter, and the nonlinear load. The IFCT with three-winding structure is installed in the vicinity of the nonlinear load. Its primary side winding (PSW) with star wiring is connected with grid, secondary side winding (SSW) with star wiring is connected with the nonlinear load, and the filtering side winding (FSW) with delta wiring is connected with SAPF. The special wiring of IFCT is to achieve harmonic magnetic potential balance between SSW and FSW, thus the PSW will drop out of such harmonic magnetic potential balance. That is to say, the harmonics are isolated away from the PSW. The detailed filtering mechanism will be discussed based on system mathematical model.

2.1. System mathematical model

According to Fig. 1, each winding of the transformer can be seen as an impedance and SAPF can be equivalent to a controlled current source in parallel with an impedance, which will be clarified later. Nonlinear loads, especially pure current-source type nonlinear load, can be described as a current source due to its infinite output impedance. Therefore, three phase harmonic equivalent circuit of the proposed IAPF are obtained in Fig. 2.

In Fig. 2, (u_{sa}, u_{sb}, u_{sc}) are grid voltages, (u_{apo}, u_{bpo}, u_{cpo}) are voltages on PSW, (u_{asn}, u_{bsn}, u_{csn}) are voltages on SSW, (u_{abf}, u_{bcf}, u_{caf}) are voltages on FSW; (i_{ap}, i_{bp}, i_{cp}) are currents on PSW, (i_{as}, i_{bs}, i_{cs}) are currents on SSW, (i_{af}, i_{bf}, i_{cf}) are currents on FSW, (i_{al}, i_{bl}, i_{cl}) are load currents; (i_{ra}, i_{rb}, i_{rc}) are SAPF reference currents, (i_{za}, i_{zb}, i_{zc}) are currents on SAPF output impedance Z_o, (i_{cat}, i_{cbt}, i_{cct}) are SAPF output currents; Z_{line} is line impedance, and grid impedance Z_g includes Z_{line} and transformer impedance. It should be noted that the voltages and currents both have fundamental and harmonic component, subscript *1* represents fundamental component and subscript *h* represents harmonic component. Besides, the load currents equal to (i_{as}, i_{bs}, i_{cs}).

Assuming that three phases are balanced and the equivalent impedances of PSW, SSW and FSW are Z_p, Z_s and Z_f, respectively. The number of PSW, SSW and FSW turns are N_1, N_2 and N_3, respectively. The magnetic potential balance equation can be expressed as,

$$\begin{cases} N_1 I_{ap} + N_2 I_{as} + N_3 I_{af} = 0 \\ N_1 I_{bp} + N_2 I_{bs} + N_3 I_{bf} = 0 \\ N_1 I_{cp} + N_2 I_{cs} + N_3 I_{cf} = 0 \end{cases} \tag{1}$$

According to Kirchhoff's current law (KCL), the current relationships among load currents, YYD-IFCT winding currents and SAPF output currents can be illustrated as follows:

$$\begin{cases} i_{ap} = (u_{sa} - u_{apo})/Z_{line} \\ i_{bp} = (u_{sb} - u_{bpo})/Z_{line} \\ i_{cp} = (u_{sc} - u_{cpo})/Z_{line} \\ i_{as} = i_{al} + i_{zal} \\ i_{bs} = i_{bl} + i_{zbl} \\ i_{cs} = i_{cl} + i_{zcl} \\ i_{ap} + i_{bp} + i_{cp} = 0 \\ i_{as} + i_{bs} + i_{cs} = 0 \\ i_{af} + i_{bf} + i_{cf} = 0 \\ i_{af} = i_{cf} + i_{cat} = i_{cf} + i_{ra} + i_{za} \\ i_{bf} = i_{af} + i_{cbt} = i_{af} + i_{rb} + i_{zb} \\ i_{cf} = i_{bf} + i_{cct} = i_{bf} + i_{rc} + i_{zc} \end{cases} \tag{2}$$

According to Kirchhoff's voltage law (KVL), the voltage relationships between YYD-IFCT winding and SAPF can be illustrated as follows:

$$\begin{cases} u_{abf} = (i_{zb} - i_{za}) Z_o \\ u_{bcf} = (i_{zc} - i_{zb}) Z_o \\ u_{caf} = (i_{za} - i_{zc}) Z_o \end{cases} \tag{3}$$

Furthermore, according to the theory of multi-winding transformer, the voltage transfer equations between PSW and FSW can be obtained as follows:

$$\begin{cases} u_{apo} - \frac{N_1}{N_3} u_{abf} = i_{ap} Z_p - \frac{N_1}{N_3} i_{af} Z_f \\ u_{bpo} - \frac{N_1}{N_3} u_{bcf} = i_{bp} Z_p - \frac{N_1}{N_3} i_{bf} Z_f \\ u_{cpo} - \frac{N_1}{N_3} u_{caf} = i_{cp} Z_p - \frac{N_1}{N_3} i_{cf} Z_f \end{cases} \tag{4}$$

Eqs. (1)–(4) describe the mathematical expressions of the system. Based on these mathematical expressions, the filtering mechanism and control strategy can be deduced.

2.2. Filtering mechanism

According to (1)–(4), the currents on PSW can be deduced as follows:

$$\begin{cases} i_{ap} = \dfrac{u_{sa}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1}{N_3} Z_o (i_{ra} - i_{rb})}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1 N_2}{N_3^2}(Z_f + 3Z_o) i_{as}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} \\ i_{bp} = \dfrac{u_{sb}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1}{N_3} Z_o (i_{rb} - i_{rc})}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1 N_2}{N_3^2}(Z_f + 3Z_o) i_{bs}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} \\ i_{cp} = \dfrac{u_{sc}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1}{N_3} Z_o (i_{rc} - i_{ra})}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} - \dfrac{\frac{N_1 N_2}{N_3^2}(Z_f + 3Z_o) i_{cs}}{\frac{N_1^2}{N_3^2}(Z_f + 3Z_o) + Z_g} \end{cases} \tag{5}$$