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# A controllable inductive power filtering system: modeling, analysis and control design☆

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ABSTRACT

This paper presents a controllable inductive power filtering (CIPF) system with the novel filtering mechanism. Due to the zero-impedance design of the power transformer, the harmonic magnetic flux between the secondary load winding and the customized filtering winding can be balanced each other. Hence, the contaminated area of harmonics is reduced. The addition of the active filter contributes to further improve the filtering performance with the task of harmonic isolation between the power grid and the load. First, the three-phase unified equivalent circuit model and the mathematical model are given out at the harmonic domain. Based on the deduced transfer matrix, the filtering evaluation criterion of CIPF system is established, and the filtering principle is revealed, as well. According to the special operational law, an improved virtual impedance control strategy is designed to prevent the potential harmonic amplification, and the relationship between the phase/magnitude of the virtual impedance and the filtering performance is discussed. Finally, the experimental results based on the laboratory scaled prototype show the validity of the CIPF system with improved virtual impedance control.

## 1. Introduction

Rapidly expanding applications of the power electronic devices inevitably introduce power quality (PQ) issues to the public grid [1–4]. Harmonic pollution and reactive power loss are the two main PQ issues existed in the three-phase power system. Harmonic may result in the malfunction of the sensitive equipment nearby the harmonic source [5]. The operating loss caused by these undesirable roving components on the electrical equipment is non-negligible, as well. For instance, the transformer may need to be derated as much as 50% capacity in the environment with the extremely distorted current waveform and low power factor [6,7]. The temperature rise due to harmonic contamination accelerates the insulation aging of the transformer, which shortens its service life [8].

To improve the power supply quality, the tuned filter (L-C) with low cost and simple structure is widely adopted to suppress harmonics and provide constant reactive power compensation in the early time [9]. Static var compensator (SVC) is later used in the industrial applications with the topology of thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) or thyristor controlled LC (TCLC), whose compensation range of reactive power can be dynamically regulated according to the load variation [10–12]. However, SVC has the disadvantage of undesirable harmonic emission. More importantly, both tuned filter and SVC have the risk of parallel/series resonance with the grid impedance [13]. With the remarkable progress in semiconductor switching devices, the research hotspot shifts to the active filtering method, which is able to overcome these negative effects [14]. Active power filter (APF) is more effective in harmonic elimination compared with passive filter. But high-power converter rating is required when used in the large power system, which inevitably makes the cost of APF quite high. The main connection schemes of APF are summarized as shown in Fig. 1 [15–25]. In type I, an additional step-down transformer is used to reduce the voltage level [15,16]. The auxiliary transformer accounts for around one-third of total weight, thus makes the filter bulky and heavy [17]. Literatures [17] and [18] present the PQ conditioner with cascade multi-level converter (CMC) to realize a small and lightweight filter in middle voltage (MV) or high voltage (HV) applications, similar like type II. In practice, the hard selection between the cascaded count and the specification of CMC module determines the cost and performance of the APF. Type III is the hybrid APF (HAPF),

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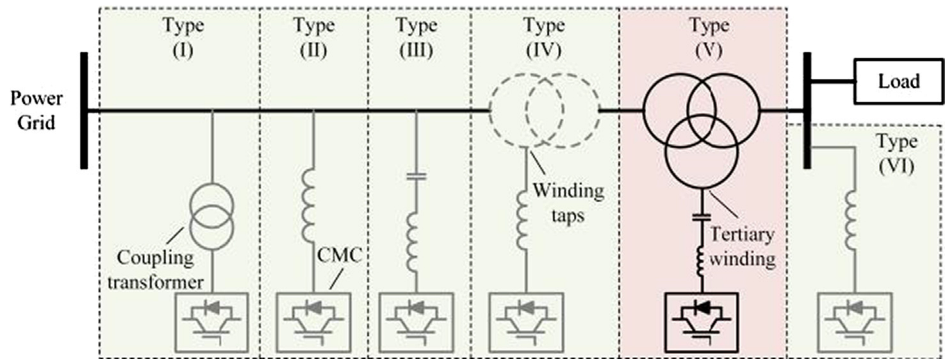


**Fig. 1.** Main connection schemes of APF.

which includes the structures of LC + APF [19–21], TCR + APF, [22], TCLC + APF, [23], etc. The main tasks for harmonic suppression and reactive power compensation are undertaken by LC or SVC, while the active part is controllable to enhance the filtering performance of the HAPF. In type III, most of the fundamental voltages drop on the passive components, so that the operating capacity of the inverter is greatly reduced. For insulation consideration, the rating voltage of the active filter should still be designed according to the voltage level at the access point (ac bus) [21]. The rated voltage of the active component in type III is still high in practice. Types IV and V which use the power transformer as the auxiliary transformer simultaneously are further derived. Type IV is called as winding-taps-injection DSTATCOM, which is connected to the taps of the primary winding [24]. The topology is easy to realize and expand. However, the compensation performance is seriously affected in the case of high load ratio.

In some high-power industrial applications, it is impossible for the filter to install at secondary side of the transformer due to the existence of large current. However, the undesirable components, in which the harmonic and reactive power are the dominant contaminant, flowing through the transformer make the operating loss high. To solve such issue, the power transformer is redesigned in [25], and a controllable inductive power filter (CIPF) using the customized filtering winding is presented as shown in type V. The equivalent impedance of the filtering winding is zero. At specific harmonic frequency, the harmonics can be canceled out between the load winding and the filtering winding, so that no harmonic is transferred into the grid winding [26]. In this way, the CIPF system can weaken the negative effect of harmonic and reactive components on the transformer. Moreover, a compromise between the voltage rating of the inverter and the initial investment is also realized by means of the filtering winding. Literature [25] proposes a comprehensive virtual impedance control to realize the zero-impedance design for implementing the inductive filtering. Furthermore, the feasibility for the CIPF applied in the shipboard power system is discussed in [27].

Totally different from the existing literatures, to further explore the filtering performance of the CIPF system, this paper mainly focuses on the following aspects.

- Establishing the three-phase equivalent mathematical model for CIPF system, which includes the transfer relationship between the grid-side current with the load harmonic current and the background harmonic voltage;
- Revealing the distinctive operational mechanism of the CIPF system in a mathematical sense, based on the obtained transfer matrices;
- Finding out the operational law. An improved control strategy is designed, and the optimal complex impedance is identified.

This paper is organized as follows. Section 2 describes the system topology and technical features of the DC supply system based on the proposed CIPF method. The mathematical model is established in Section 3. Section 4 analyzes the operational mechanism and the filtering performance. Moreover, Section 5 presents an improved control strategy, and the filtering ability is further investigated. Section 6 gives the experimental results. Finally, the conclusion is given in Section 7.

## 2. System topology

Fig. 2 shows the new DC supply system based on the CIPF method. Different from the conventional filter, CIPF (blue area) is installed behind the PCC/primary bus. As the key equipment for implementing the inductive power filtering (IPF) method, the new transformer, which has a three-winding structure, is configured in the vicinity of the rectifier bridge. Besides, its primary winding adopts the star wiring, and is connected with the public power system (red area). The secondary winding of the new transformer adopts the extended-delta wiring, which not only provides a close delta loop for the zero-sequence current, but also has the merits of high capacity utilization and easy to realize phase shift. The extended winding connects to the rectifier load (green area), and serves as the load winding. For each phase, there is a linking point between the delta winding and the extended winding. The three parallel filtering branches access to the new transformer via the linking point. The main distinction between the IPF and the CIPF is the configuration of filtering branches. In this paper, the proposed CIPF uses a 5th single-tuned filter and a series voltage-source inverter (VSI) as the filtering branches.

The proposed DC supply system has the following technical features: (1) The filtering system takes the full advantage of IPF method to reduce the most effects of harmonic on the transformer. The flowing path of the harmonic current is restricted in a small area, so that the purity of the grid-side current waveform can be satisfied; (2) Thanks to that the filtering winding can be customized for the practical application, the controlled VSI can directly access to the transformer at an acceptable voltage level without additional auxiliary transformer. (3) Hybrid filter further cuts down the capacity of active filter dramatically by sharing the main task of harmonic suppression with the passive filter. (4) With the adoption of the virtual impedance control, it can make up the IPF's defects to withstand the external fluctuation and further mitigate the impact of harmonics from the grid.

## 3. Mathematical modeling

### 3.1. Basic current transitive relation

Referring to Figs. 2 and 3, and according to the principle of ampere-turns balance, the winding currents in the new transformer should satisfy the following relationship, that is