Historical Review of Parallel Hybrid Active Power Filter for Power Quality Improvement

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***Abstract*—Hybrid active power filter (HAPF) has already been an effective and widely-used method for power quality improvement. This paper presents historical review and developing progress of the HAPFs' functionalities as harmonic and reactive power compensation. The structures of HAPFs are discussed in different historical periods, and divided into four developing pattern: parallel active part with parallel element, parallel active part with series element, b-shape, and three-phase four-wire structure. It is aimed at making a comprehensive analysis of HAPFs' historical developing tendency in structure and function design. The future possible developing guidelines are discussed as conclusion in the last.**

***Keywords*— Current harmonics; hybrid active power filter (HAPF); reactive power**

I. Introduction

Due to the advancement of technology, industrial structure reforming, and the development of smart grid technology recently, people have a higher demand for improved power quality [1]. However, with the proliferation and increased use of power electronics devices and motor loading, it is becoming more difficult to achieve this goal [2]-[10].

In mid 1940s, passive power filters (PPF) were developed to suppress current harmonics and compensate reactive power [11]. In 1976, active power filters (APF) were developed to compensation harmonics. HAPFs are more attractive in harmonic filtering than pure APFs from both viability and economical view [12][13]. To achieve the best performance, the united power quality converter (UPQC), has been developed with an extremely high cost [14].

During 1967~2005, HAPFs are mainly applied to traditional industry, such as steel furnace, ASD, etc. Most research works focus on basic and single function, just harmonic compensating.

After 2005, many researchers focus on the development of application, optimal design, and dynamic reactive power compensating. Some literatures [15]-[18] have discussed the feasibility of HAPF in railway, wind farm, and photovoltaic generator. As the price and operating loss of power electronic switcher limit the performance of HAPF, many researchers have proposed optimal design method in parameter selection [19], control method [20][21], and structures.

Many review papers make a comprehensive summary of HAPF. In 2000, "Active power filters: A review" classified the research work published in five aspects: power rating and respond speed, configuration and connection, compensated system parameters, control techniques, reference signal estimating technique [22]. In 2005, "Hybrid filters for power quality improvement" summarized the most HAPF structures based on different combination of AF and PF. The selection criteria are also list in details [23]. In 2005, "Active harmonic filters" discussed the performance of three HAPF in detail: the hybrid of active shunt and passive series, the hybrid of active series and passive shunt, transformerless LC-HAPF [24]. In 2012, "A Comprehensive Analysis of Hybrid Active Power Filter for Power Quality Enhancement" divided ten HAPFs in two aspects: shunt filter and series filter. Five basic control method are also discussed in this paper, as Fourier transform, Synchronous reference frame, Instantaneous reactive power theory, High-pass filter method, Low-pass filter method, and Adaptive linear neurons control [25]. In 2013, "Review of Hybrid Active Power Filter Topologies and Controllers" divided all HAPFs based on topology, converter configuration, supply system, passive filter type and listed some new control methods in harmonic detecting and controller technologies [26].

This paper aims at presenting the developing progress of HAPF structures. By summarizing the different historical period of HAPF development, the inner thought and future research work of development can be analyzed. In this paper, there are four sections. The section I is the introduction. In Section II~III, the development of different HAPF in each period are discussed in the items of functionality and structure. In section IV, the conclusion of future development of HAPF is discussed.

II. Functionality

The historical periods of the development of HAPF function can be divided into three strategies: origin stage, developing stage and mature stage. The main research work of the functionality of HAPF in each historical period are presented in Fig.1.

A. Current Harmonic Compensation

Harmonic compensation is the most basical and earliest function of HAPF. 1976~1995 is the origin stage. During this period, researchers began to use HAPF to damping balance current harmonic. In this period, HAPFs were thought to be only suitable in low-and medium-voltage system and benefit in damping harmonic resonance [27].

In 1996~2005, the function of harmonic compensation came into developing period. Three main directions, like high-voltage application, damping harmonic resonance, and unbalance harmonic compensation, have been proposed.

In 2005~now, it can be called mature period. Most papers focused on three aspects: renewable source, multi-function, and optimal design. Some published research work on the

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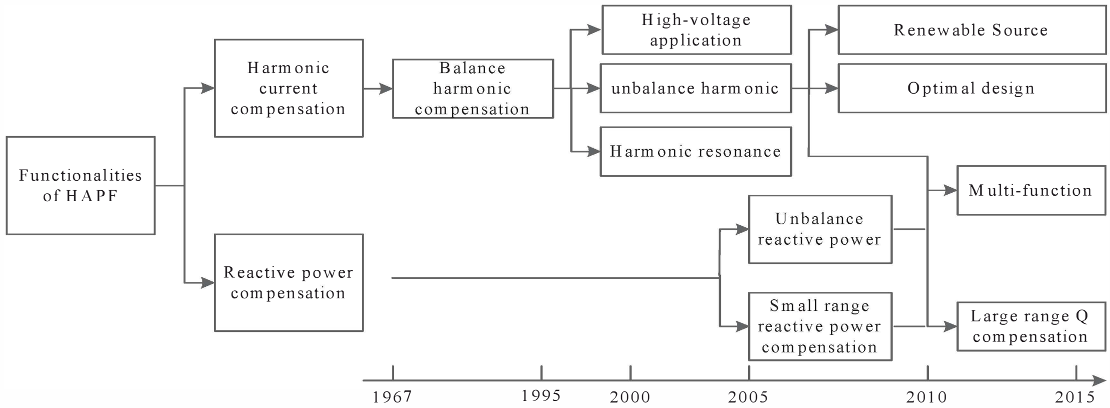

Fig.1 Development of the functionalities of HAPF

harmonic compensating of HAPF focus on some new application, such as high speed railway [15], photovoltage generator [17] and wind farm [16].

B. Reactive power compensation

Reactive power can be compensated using Var generators. The technology developments of this function are far behind the function of harmonic compensation. The historical period of development in this function can be mainly divided in three strategies.

Before 2005, Some researchers think this technique would only be suitable for low-power application and a waste of sophisticated equipment to tackle them without the use of other power-factor-correction device[28].

During 2005~2009, the alternative of reactive power compensation of active filter was first presented in [29]. The functionalities of HAPF have harmonic current, small range of dynamic and unbalance reactive power, which are more suitable for medium- and low-voltage application.

2009~now, many research work about this multiple function of HAPF in different applications have been reported [30]. To expand the range of reactive power compensation, the combination of shunt HAPF and other controllable reactive power compensating circuit are proposed in [31].

III. STRUCTURES

Based on the type of combination, the structures of HAPF are divided in four aspects: parallel APF and parallel element; parallel APF series with element; b-shape HAPF; neutral-line compensation structure. Fig.2 shows the development of HAPF structure in past decades.

A. Parallel active part and parallel compensator

The development of this structure has two historical periods, classified based on the parallel element. The structure of two parallel elements have the benefit of stability as these two elements are independent of each other.

A.1 Uncontrollable parallel compensator

In 1967~2011, it can be called the period of uncontrollable parallel compensator. Fig.3 show the typical structure of parallel APF and uncontrollable element. It is a mixture of parallel APF and PPF [32]. The APF part is designed to compensate high-order current harmonics, and the PPF part is used to compensate the larger-capacity and low-order harmonics. This structure has two drawbacks as high operating loss and initial cost.

A.2 Controllable parallel compensator

2012~2015, can be called the period of controllable parallel compensator. In this period, many controllable elements, such as full-bridge converter, TCR, etc., are used to instead of traditional uncontrollable element. Compared with last generation, the controllable parallel elements provide a better performance for dynamic compensating.

The literature [33] presented a combination of low- and high-frequency HAPF to operate in parallel for better performance in 2012. The structure can be shown as Fig.4. The dc links of both the inverters are connected in parallel, and DC voltage is maintained by the low-frequency inverter. This structure has a wide harmonic compensating range with less switchers.

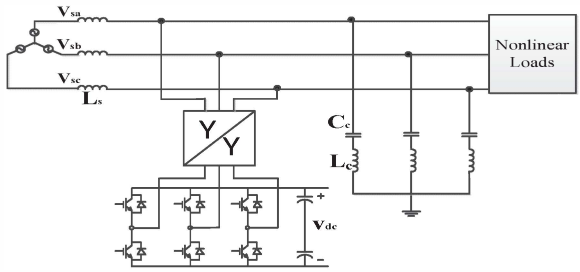

Fig.3 Parallel APF and PPF

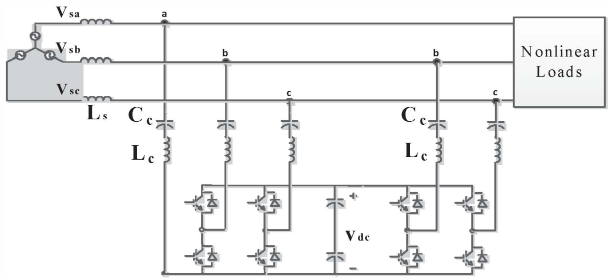

Fig.4 Combination of low- and high-frequency HAPF

The literature [34] presented a structure of parallel APF and a parallel TCR circuit in 2013, as shown in Fig.5. This structure can be useful for asymmetrical and nonlinear loads in the function of current harmonic.

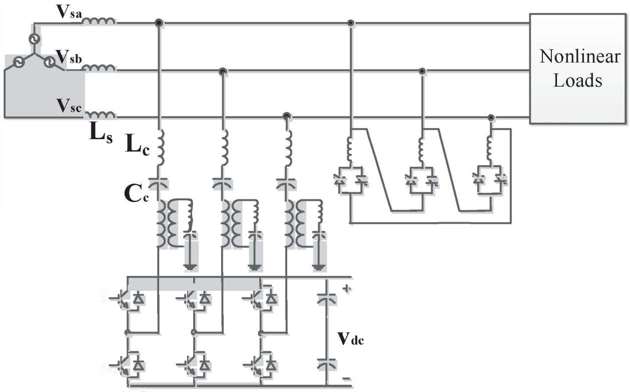

Fig.5 Injection-HAPF parallel with TCR

B. Parallel active part series with element

The structure of parallel active part series with compensator normally have less operating loss. But each part of the configuration affects each other. Based on the series element, there are three main historical period of this structure type, divided as transformer and parallel element.

B.1 Uncontrollable series compensator with transformer

In 1990~2000, many research work use the structure of LC-HAPF with transformer structure, as shown in Fig.6 [35]. In this structure, the APF connect with a coupling LC part in series through a transformer. It is especially suitable for medium- and high-voltage applications, as the passive part reduces the fundamental voltage applied to switchers.

B.2 Uncontrollable series compensator without transformer

In 2001~2013, with the development of power electronic switcher, higher-voltage IGBT has already been available [36]. It make possible that the active filter can be connected to passive filter directly without a transformer. Compared with last generation, the initial cost in this period is reduced largely.

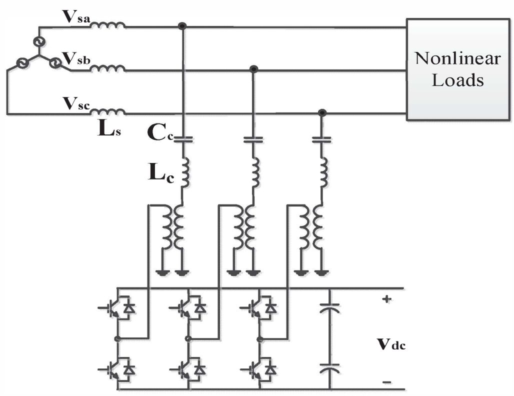

Fig.6 HAPF with transformer

The literature [37] presented a combination of parallel IGBT converter and parallel MOSFET converter in 2013, as shown in Fig.7. The function of the IGBT converter support fundamental voltage and compensate the fundamental reactive power. The MOSFET converter fulfills the function of harmonic current compensation [37]. This structure has a wide compensating range. But it has very high initial cost due to the 12 switchers.

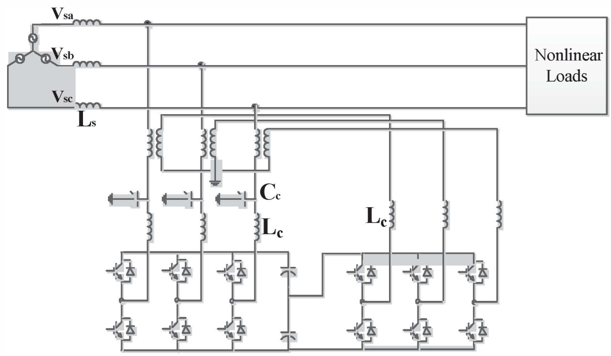

Fig.7 IGBT converter series with MOSFET converter

The typical transformerless HAPF is proposed in 2003, as shown in Fig.8 [36]. This structure has been widely used in industry. It is effective in harmonic and reactive power compensating. While, the compensating range of reactive power is limited as the fixed LC circuit.

B.3 Controllable series compensator without transformer

In 2014~2015, the structure of controllable series compensator is proposed. The literature [38] firstly presented a combined system of a thyristor controlled reactor and a shunt hybrid power filter in 2014, as shown in Fig.9. By using the FC-TCR circuit, this structure has a larger reactive power compensating range than the last generation.

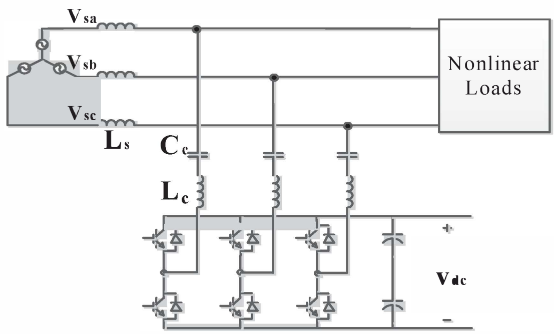

Fig.8 Transformerless HAPF

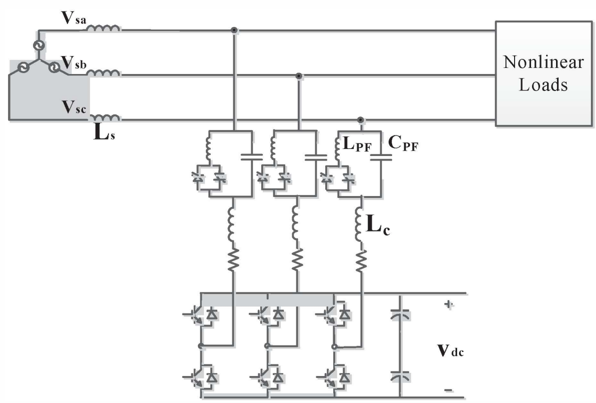

Fig.9 Transformerless HAPF series with TCR

C. b-shape HAPF

A b-shape type is defined as 2 external elements connected in series and one of them is in parallel with active filter. Due to the shunt branch, the current rating of active part is less than normal structure. While, the performance of harmonic part of the compensating current will flow into the external branch.

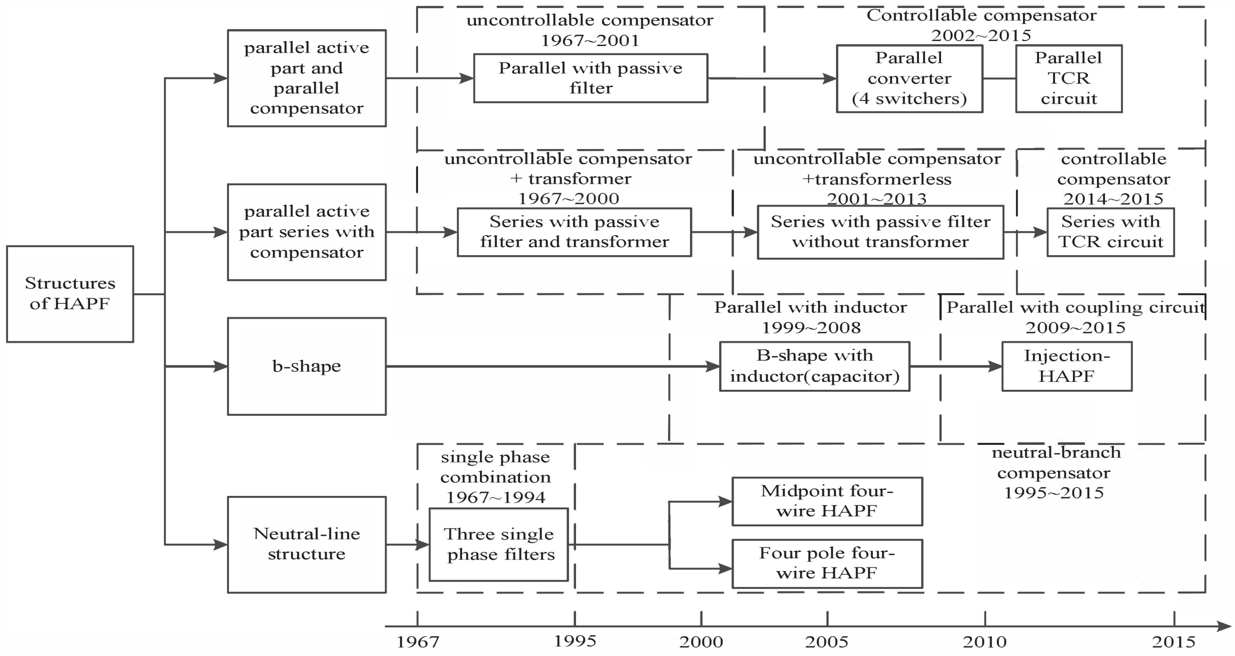

Fig.2 Development of the Structures of HAPF

C.1 Parallel with Inductor

In 1999~2008, typical b-shape structure is a combination of a series connected capacitor and a parallel connected inductor with active part. In 1999, the literature [39] first presents b-shape HAPF as shown in Fig.10. The parallel branch can largely reduce the rating of active part as the value of inductor is small. While, it requires a large inductor to compensate fundamental reactive power.

C.2 Parallel with fundamental coupling circuit

In 2009~2012, a novel b-shape HAPF is presented as shown in Fig.11 [40], which is called as injection-HAPF. The injection circuit of this structure is a combination of a series connected capacitor and a parallel connected fundamental coupling circuit. This system has a very low DC voltage as the parallel branch can reduce fundamental voltage largely. As the fundamental voltage of active part is nearly zero, this structure can not compensate dynamic reactive power.

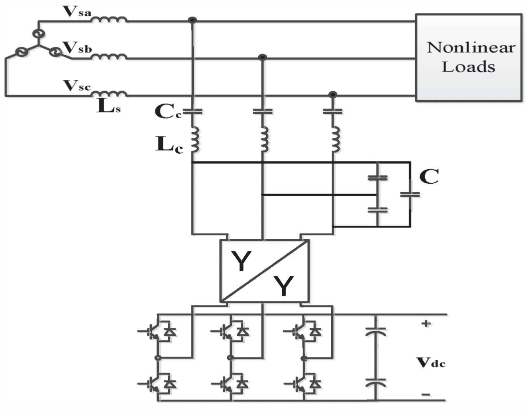

Fig.10 b-shape HAPF with capacitor

D. Neutral-line compensation structure

For three-phase four-wire system, the harmonic in neutral line should also be considered. Right now, there are three typical and widely accepted structures

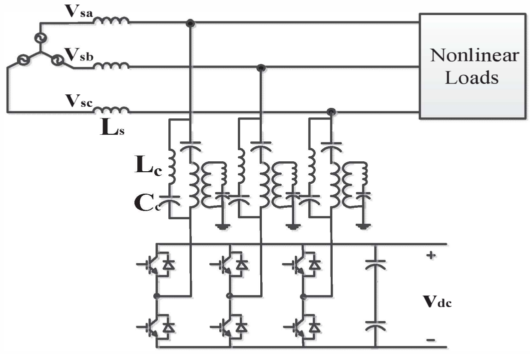

Fig.11 Inject-HAPF

D.1 Combination of Single-Phase Compensator

Before 1994, most researchers use the multi-combination of single-phase HAPF to compensate the harmonic current in three-phase four-wire system [41]. Fig.12 show the typical structure. This structure has a good performance in unbalance harmonic compensating without a complex control method. While, this structure need so many switchers that the initial cost and operating loss are both very high.

D.2 Neutral-Branch Compensator

1995~2015 can be called as the period of neutral-branch compensator. Two novel structures, midpoint four-wire and four-pole four-wire HAPFs were proposed and widely used in three-phase four-wire system with less switchers, as shown in Fig.13 and Fig.14 [42]. The capacitor mid-point HAPF is always used in small rating as the neutral current through DC capacitor may be a large value. The four-pole HAPF is suitable for medium-voltage application as the neutral harmonic current can be compensated by the external bridge.

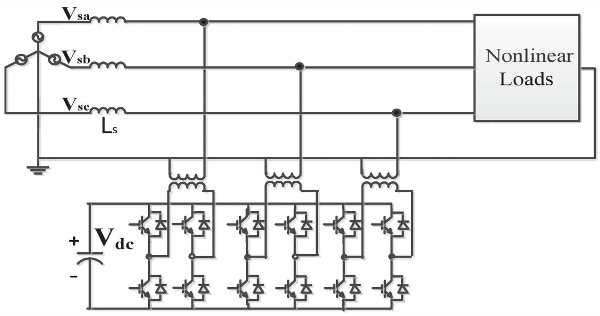

Fig.12 Combination of single-phase HAPF

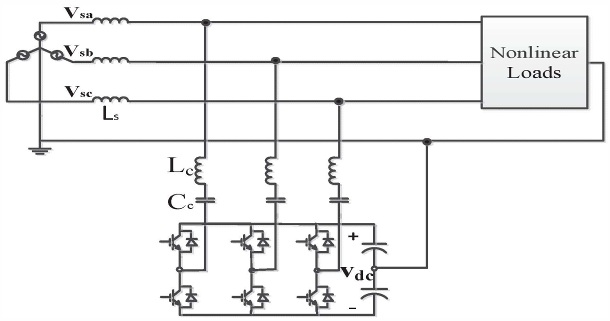

Fig.13 Midpoint-HAPF

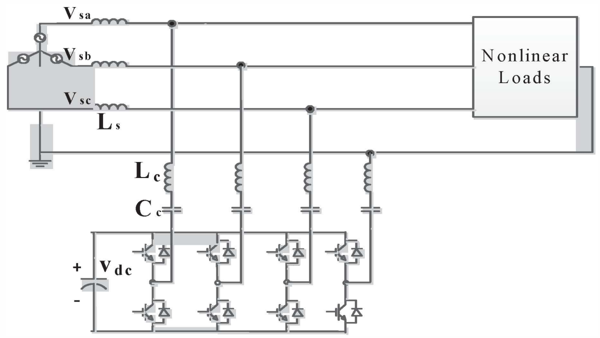

Fig.14 Four-pole HAPF

IV. Conclusion

In the whole historical developing progress of HAPF, its functions have been evolving from single compensating item to multi-items, and the combined element of structures have also been evolved with more controllable elements instead of traditional uncontrollable elements. Table I shows the comparison of each typical structures for functionality, initial cost and operating loss. In the future, the possible developing trend of HAPF can be expressed as two guidelines:

1)HAPF can compensate three items, as harmonic, fundamental reactive power and fundamental active power.

2)Combination of multi-controllable-compensators.

TABLE I. Comparison of Functionality, Initial Cost and Operating Loss

		Functionality		Initial Cost	Operating Loss	
		Dynamic Q	Harmonic		DC voltage	Switcher Number
APF+PPF(Fig3)		Y	**	*	**	6(IGBT)
Two parallel HAPF(Fig.4)		Y	***	***	*	8(IGBT)
Injection HAPF +TCR(Fig.5)		Y	*	**	**	6(IGBT)
HAPF with transformer (Fig.6)		Y	*	**	*	6(IGBT)
IGBT active filter series with MOSFET filter (Fig.7)		Y	**	***	*	6(IGBT)+ 6(MOSFET)
HAPF without transformer (Fig.8)		Y	*	*	*	6(IGBT)
HAPF series with TCR(Fig.9)		Y	*	**	*	6(IGBT)+ 6 (Thyristor)
B-shape HAPF (Fig.10)		Y	*	*	*	6(IGBT)
Injection HPAF (Fig.11)		N	*	**	*	6(IGBT)
3P4W	Single phase HAPF (Fig.12)	Y	**	****	**	12(IGBT)
	Mid-point HAPF (Fig.13)	Y	*	*	*	6(IGBT)
	Four-pole HAPF (Fig.14)	Y	**	**	*	8(IGBT)

Configuration with higher number of * means better performance in functionality, higher initial cost and higher DC voltage. Y means Yes and N means No.

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