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厦门大学

博　士　学　位　论　文

一种新型并联混合型有源电力滤波器的研究

Study on A Novel Shunt Hybrid Active Power Filter

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摘 要

随着越来越多的非线性负载被应用到工业生产中，电网受到的谐波污染日益加重，因此对谐波治理的研究愈发受到重视。工业上抑制谐波畸变最常用的方法是采用无源滤波器（passive filter，PF），但是 PF 存在补偿效果对负载有依赖性、使用不够灵活、容易引发串联和并联谐振等缺点。有源电力滤波器（active power filter，APF）能够克服 PF 的缺点，被认为是解决电力系统谐波问题最有前途的方法之一，但是其成本较高。混合型有源电力滤波器（hybrid active power filter，HAPF）兼具 APF 与 PF 的优点，因此得到广泛关注。

论文在深入分析混合型有源滤波器研究现状的基础上，以实现工厂低压配电系统大功率滤波与无功补偿为目标，提出一种新型并联混合型有源电力滤波器并对其关键技术进行了研究，解决了电流优化控制、阻尼电网谐波电压、直流侧电容电压控制和补偿不平衡负载等问题，完成了工程样机的研制与调试。具体研究内容和创新点如下：

1) 拓扑结构的提出、电气模型建立与滤波原理分析

在对混合型有源滤波器设计原则归纳分析的基础上，以实现工厂低压配电系统大功率电流滤波与无功补偿为目标，提出一种基于无变压器并联混合型有源电力滤波器（transformerless shunt hybrid active power filter，TLS-HAPF）与晶闸管投切单调谐无源滤波器（thyristor switched passive filter，TSPF）联合运行的新型并联混合型有源电力滤波器，继而描述了系统各部分的构成，阐述所提出的拓扑结构的优势，建立新拓扑结构的电气模型，从负载电流检测模式与电源电流检测模式两个方面分析系统滤波原理，通过仿真和实验验证了新拓扑结构的补偿能力。

2) 基于无源性理论的电流控制算法研究

新型滤波器的滤波效果取决于谐波电流跟踪控制性能。常规电流跟踪控制方法将 TLS-HAPF 视为一个线性系统处理，忽略了其本质非线性，这在系统受到扰动时会产生电流畸变，甚至引发不稳定。无源性理论将一个动态系统视为一个能量转换装置，通过重新分配系统的能量和注入非线性阻尼，使系统在满足无源

性条件的情况下达到要求的性能。提出将无源性理论应用到 TLS-HAPF 的电流控制中，首先建立系统的数学模型，继而通过注入阻尼获得原系统的伴随系统及跟踪偏差的动态方程，论证系统的严格无源性，推导得到基于无源性理论的控制律，给出了控制框图并将其应用到系统控制中，仿真和实验证明了无源性理论的正确性。

3) 电网电压谐波阻尼复合控制的研究

电网电压谐波阻尼是指 APF 检测接入点的电网谐波电压然后乘以一个系数形成指令电流并输出，用以防止由谐振效应产生的谐波扩散。针对新型滤波器中的有源部分提出了基于电压谐波检测的谐波阻尼控制算法，继而将其加入到电流补偿型有源滤波器中，构成了基于负载谐波电流补偿和电网电压谐波阻尼的复合控制，用以同时补偿负载谐波电流、阻尼电网谐波电压、抑制无源滤波器和电网之间可能产生的谐振。同时，为了保证系统的稳定性，提出一种优先保证谐波阻尼控制的输出电流限流方法，通过引入谐波电流补偿增益系数 K_i 实现对输出电流的调节，使输出电流始终保持在最大允许电流范围内。

4) 新型滤波器应用技术研究

对新型滤波器应用中的两项技术--直流侧电容电压控制和补偿不平衡负载进行了研究。直流侧电容电压的稳定是有源滤波器正常工作的前提，通过对 APF 的适当控制其可自行建立直流侧电容电压并使之保持稳定，提出一种电容电压单闭环控制策略，实现了电容电压与补偿电流控制器参数的解耦，简化了参数的整定，优化了控制效果；对于三相系统，当存在不平衡的相间负载时，会在电网电流中引入负序分量，使用有源滤波器补偿负序电流会大大增加容量，提高系统造价，因此本文提出了一种带有负序电流分离的谐波电流检测策略，实现了不平衡负载环境下的谐波补偿。

论文设计了新型滤波器工程样机并进行了相关实验研究。搭建包含电网、非线性负载、非平衡负载、感性负载和电网电压谐波源的实验系统，将工程样机分为功率电路、控制电路和柜体结构等部分进行设计，完成了相关电路的调试与控制程序的编写，将提出的控制方法应用到工程样机中，通过电能质量分析仪记录实验数据。实验结果表明，新型混合滤波系统工作稳定，补偿效果优异。

关键词：混合型有源滤波器；无源性；谐波阻尼；电容电压控制；不平衡负载

Abstract

As more and more non-linear load is applied to industrial production, harmonic propagation has become a serious problem in power distribution systems the most commonly used method of harmonic compensation is passive filter (PF), but PF has many disadvantages, such as the compensation effect dependence on the load, not flexible enough to use, easily lead to series and parallel resonance and so on. Active Power Filter (APF) is able to overcome the shortcomings of PF and is considered to be one of the most promising way to solve the power system harmonic problems, but the cost of APF is very high. Hybrid active power filter (HAPF) combines the advantages of APF and PF, so it is getting widespread attention.

Through the in-depth analysis of developments and trends of HAPF, this paper proposes a novel shunt hybrid active power filter and deliberates its key technologies in order to achieve high-power filtering and reactive power compensation against low-voltage distribution systems, solves a series of problems, such as the optimization of current control, damping out the harmonic of power grid voltage, the voltage control of DC capacitor and the compensation of unbalanced load, completes engineering prototype debugging. Specific research contents are as follows:

1) The propose of the topology, electrical modeling and filtering principle

Through the summary of the design principle of HAPF, this paper analyses the harmonic characteristics and the demand of industrial filter, proposes a novel shunt hybrid active power filter based on a combined system of transformerless shunt hybrid active power filter (TLS-HAPF) and thyristor switched single-tuned passive filter (TSPF) in order to achieve high-power filtering and reactive power compensation against low-voltage distribution systems, describes the constituted portion of the system, expounds the advantages of the proposed topology, and then establishes the electrical model of the topology, analyses the filtering principle of the system. Compensation effect of the proposed topology is verified by simulation and experiment.

2) A novel passive control strategy for TLS-HAPF

Conventional control methods seem the TLS-HAPF as a linear system, they ignore its essential nonlinear nature, the output current will distort when the system is disturbed, and even lead to instability. Passive theory seems a dynamic system as an energy conversion device, through reallocation energy and injecting nonlinear damping, forces the system to meet the performance under passive conditions. This paper proposes a passivity control strategy for TLS-HAPF. First, the shunt hybrid power filter is modeled in the stationary abc frame and then the model is transformed to the rotating dq frame with the aim of reducing the control complexity. Then by means of injecting adjustable damping into the system to establish its adjoint system and get the tracking error dynamic equation. The storage function of the closed-loop system is established and derivated to prove its strictly passivity. Finally, the dynamic controller is derived from the adjoint system and the control graph is given. The simulation performed in MATLAB and experimental results verify the validity of the new approach.

3) The study on damping out the harmonic of power grid voltage and compound control

Damping out the harmonic of power grid voltage means APF detect the harmonic voltage of common coupling point, multiply by a factor to form a reference current and then output, the damping can prevent the harmonics diffusion generated by the resonance effect. This paper proposes the damping control for TLS-HAPF based on the voltage harmonics detected, and then the damping control is added to the current compensation algorithm to form compound control. The compound control could inhibit the resonance may be generated between the passive filter and the grid inductance, it improves the of the system. For the sake of stability, this paper proposes a current limiting compensation scheme which gives priority to damp out the harmonic of power grid. This method is designed to ensure the output current is always kept at the maximum allowable range by introducing a K_i to the reference current.

4) The study on key techniques for engineering application

The research study on two key technologies, they are the voltage control of DC capacitor and the compensation of unbalanced load. The stability of the DC capacitor voltage is the premise of the active filter working properly, APF could form the DC capacitor voltage by itself and keep it stable. This paper proposes a single-loop voltage control strategy and achieves the decoupling between capacitor voltage controller and compensation current controller, the new controller simplify the setting of parameters and optimizes the control effect. The negative sequence current will be introduced to the system when there is an imbalance load between the phases for the three-wire system. Using APF to compensate negative sequence component in the grid current will greatly increase capacity of filters and boost the cost. In this paper, a harmonic current detection strategy which could separate the negative sequence current from the total is put forward to achieve the harmonic compensation under unbalanced load.

Finally, the research focuses on engineering implementation of the novel topology. Experiment system that contains the grid, nonlinear load, unbalanced load, inductive load and voltage harmonic source have been performed. Then active filter is designed and connected to experiment system, all the strategy are employed in APF. Experimental results recorded by a three-phase power quality analyzer show the novel shunt hybrid active power filter works stably and the compensation effect is excellent.

Keywords: Hybrid Active Power Filter; Passive Control; Harmonic Damping; Voltage Control of DC Capacitor; Unbalanced Load

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