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厦门大学

硕　士　学　位　论　文

基于观测器理论的选次谐波检测与补偿

Selective Harmonic Detection and Compensation Based on Observer Theory

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摘 要

近年来电网谐波污染日益严重，谐波的研究和治理受到了国内外的高度重视。为了实现谐波的选次、精确补偿，本文分别对谐波检测和有源电力滤波器（APF）的控制策略两部分内容进行了研究。首先，观测器理论运用在谐波检测领域的研究，国内外学者才刚开始涉及。本文提出了一种基于观测器理论的新型谐波电流检测方法，实现了指定次谐波的快速、精确检测，为谐波检测提供了一种新的思路；其次，工业过程中环境干扰给系统的结构参数带来很大的不确定性，按照理想模型设计的最优控制器在此情况下难以保持最优。本文设计了一种自适应的模型预测控制方法，能够计算出电路参数变化给系统模型带来的偏差，在等效的实际电路模型上实现逆变器的精确电流跟踪；最后，结合两部分内容研究了 APF 的选次谐波补偿策略，并完成了仿真验证和实验调试。具体的研究内容和创新点如下：

提出了一种基于观测器理论的新型电流谐波在线检测方法。首先，负载电流可以看做是由基波和前 n 次谐波分量之和组成的，因此该方法将待测电流写成傅里叶级数的形式，将电流通过一个积分环节构成一个动态系统。然后，将基波和谐波参数作为状态量，建立状态方程，设计观测器将指定次谐波参数在线检测出来，利用 Lyapunov 定理和 Lasalle 不变集原理证明了观测器的收敛性。最后，将观测器方程离散化，得到了每个控制周期谐波检测的控制律。该方法不仅可以用于单相电路，还可以用于三相电路中每一相的谐波检测；与传统瞬时无功功率相比，不仅可以检测总谐波电流，而且可以检测指定频次谐波分量；与 FFT 方法相比，检测谐波具有准确性；与神经网络自适应预测算法以及 Ip-Iq 算法相比，当电流发生突变时，本方法谐波检测速度更快，具备很好的动态性能；另外，本方法对噪声具有很好的抗干扰性。仿真结果论证了以上特性。

设计了一种自适应的模型预测控制方法解决逆变器的电流跟踪问题。这种方法通过计算电路参数变化给控制模型带来的偏差，建立等效的实际电路模型，为实现精确的电流跟踪打下了基础。这种观测偏差的算法简单，能够在线、迅速地进行参数辨识。仿真结果验证了本方法对电路参数辨识的准确性较好、响应迅速。在全桥逆变器的电流跟踪控制中，结合参数偏差消除的自适应原理，使用模型预

测控制方法实现了电流的精确跟踪。仿真分析证明使用自适应的模型预测控制方法比仅仅使用模型预测控制具有更精确的跟踪效果、跟踪误差小，同时能够快速地应对负载变化、动态性能好，计算时间少。

实现了 APF 的选次谐波补偿。首先阐述了谐波电流检测和补偿的实现原理，通过单相谐波补偿的仿真分析，直观的验证了所提方法对选次谐波补偿、谐波补偿程度能够单独设置、各选次谐波精确补偿 3 方面功能的满足。然后搭建了 APF 谐波检测与补偿的总体实验，设计了主控运算、信号检测与调理、逆变器及其驱动和硬件保护模块等，给出了软件总体设计思想以及各个模块程序的设计方法。实验结果验证了所提方法可以实现谐波补偿频次可选、且谐波补偿具有很好的准确性。仿真和实验均验证了本文提出的谐波检测方法和补偿具有准确性高、响应迅速、计算时间短的优点，而且能够很快的适应负载的变化，动态性能好。

关键词：观测器；有源电力滤波器；谐波检测；谐波补偿

Abstract

In recent years, the power network's harmonic pollution becomes more and more serious. The study and governance of harmonic absorb high attention in the world. In order to realize selective and accurate harmonic compensation, harmonic detection and control strategy of APF are studied in this paper. Firstly, it's just the beginning for the foreign scholars to involve the research of observer theory applying in the field of harmonic detection, which is a blank field in China. This paper puts forward a new method in harmonic current detection based on observer theory, which has realized the fast and accurate detection of specified harmonic, providing a new way of thinking for harmonic detection. Secondly, in the process of industry, environmental disturbance brings a big uncertainty to the structural parameters of multiple systems. It's difficult to keep optimal for the optimal controller designed according to the ideal model in this situation. So this paper designs a control method of adaptive model prediction, which can calculate the deviation of system model brought by the change of circuit parameters. Therefore it can realize the precise current tracking of inverter on the equivalent of actual circuit model. Finally, combining two parts of above content, this paper studies the strategy of selected harmonic compensation of APF and finishes the simulation verification and experiment debugging. Specific research contents and innovation points are as follows:

This paper proposes a new type of method for on-line current harmonic detection based on the observer theory. Firstly, the load current can be regarded as a combination of a direct current, a fundamental componentand the sum of harmonic components of first n times. Because of that, this method puts the current-to-be-measured into the form of Fourier series, and builds a dynamic system by integrating the current. Secondly, regarding the fundamental and harmonic parameters as state variable, a state equation is established and an observer is designed to detect the parameters of specified harmonic online. By Lyapunov theorem

and Lasalle invariant set principle, this paper proves the convergence of the observer. Thirdly, this paper discretizes the observer equation, and gets the control law of harmonic detection in each control period.This method can be used not only in single-phase circuit, but also in the harmonic detection of each phase in three-phase circuit. Compared with the method of traditional instantaneous reactive power, this method can detect not only the total harmonic current, but also the specified frequency harmonic component. Compared with the FFT method, this method is more accurate in detecting harmonic. When the currents conflict, compared with the neural network and Ip-Iq algorithm, this method is faster in harmonic detection, and has good dynamic performance. In addition, this method has good anti-jamming for noise. The simulation results demonstrate the characteristics above.

This paper designs a control method of adaptive model prediction for the current tracking problem of inverter. This method can calculate the deviation of control model brought by the change of circuit parameters, and then establishes the equivalent of actual circuit model, laying the foundation of precise current tracking. This algorithm is simple and can identify the parameter online and quickly. Simulation results demonstrate that this method has good accuracy and quick response in circuit parameter identification. In current tracking control of the full bridge inverter, combining with the adaptive principle of eliminating parameter deviation, the model predictive control method realizes the precise tracking of current. Simulation analysis proves that its tracking performance is more accurate and tracking error is smaller than model predictive control individually. It can quickly respond to load change and has good dynamic performance and less computation time.

This paper realizes the selective harmonic compensation of APF. Firstly, this paper expounds the principle of harmonic detection and compensation. Through the simulation analysis of single-phase harmonic compensation, it intuitively verifies that this method can meet the three functions: selective harmonic compensation, harmonic compensation degree can be set separately and precise compensation of each selected

harmonic. Secondly, the overall experiment of APF harmonic detection and compensation is built. The control module, signal detection and modulation module, inverter and driver module and hardware protection module are designed. At the same time, the overall design idea of software and design methods of program for the various modules is presented. The experimental results validate that the proposed method can realize the optional harmonic compensation frequency, and the harmonic compensation has a very good accuracy. Simulation and experiment verifies that the harmonic detection methods and compensation proposed in this paper has the advantages of high accuracy, rapid response and short computing time, and can quickly adapt to the change of load, and has a good dynamic performance.

Keywords: Observer; Active power filter; Harmonic detection; Harmonic compensation

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