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Adaptive fuzzy backstepping control of three-phase active power filter

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ABSTRACT

A backstepping controller (BC) and an adaptive fuzzy backstepping controller (AFBC) are proposed for three-phase active power filter (APF) in this paper. Firstly, the dynamic model for APF is build in which both the system parameter variations and external disturbance are considered. Then, the backstepping method is applied in the design of current control system to deal with the nonlinearity of APF. Moreover, the AFBC is developed by combining the backstepping approach with adaptive fuzzy strategy to attenuate the effect of parameter uncertainties and external disturbances. Fuzzy logic system is designed to estimate the unknown nonlinear function in the AFBC where the parameters are adjusted online by the adaptive law derived from the Lyapunov stability analysis to guarantee the tracking performance and stability of the closed-loop system. Simulation studies using the MATLAB/SimPower Systems Toolbox demonstrate that the proposed control strategies exhibit excellent performance in both steady state and transient operation.

1. Introduction

Nonlinear loads often bring harmonic-related problems to the industrial power systems including low power factor, phase distortion, waveform surges and so on. Shunt active power filters are the most widely used solution because they can efficiently eliminate current distortion and the reactive power. The APF operates by injecting compensation current which is of the same magnitudes and opposite phases with the harmonic currents into the power system to eliminate harmonic contamination and improve the power factor. Compared with conventional current control methods including hysteresis control, single cycle control, space vector control, and repetitive control, many new control strategies have been designed to improve the dynamic response, such as fuzzy control, neural network control, sliding mode control, and adaptive control. Braiek, Fnaiech and Haddad (2005) improved the control of an APF using feedback linearization technique by using power balance in source side and APF sides. Komucugil and Kukrer (2006) presented a new control strategy for single-phase shunt active power filters (SAPF) based on Lyapunov stability theory. Rahmani, Mendalek, and Haddad (2010) proposed a nonlinear control technique for a three-phase SAPF and tested it on a laboratory prototype of an SAPF. Shyu, Yang, Chen, and Lin (2008) introduced a model reference adaptive control for a single-phase SAPF. Matas, Vicuna, and Miret (2008) developed the feedback linearization technique for a single-phase SAPF. Montero, Cadaval, and Gonzalez (2007) compared different methods for extracting the reference currents for SAPF in three-phase four-wire systems. Valdez, Escobar, and Ortega (2009) showed an adaptive controller for a single-phase APF to compensate the current harmonic distortion. Marconi, Ronchi, and Tilli (2007) designed a robust nonlinear controller for SAPF to absorb harmonics. Hu, Shi, Lu, and Xing (2012) introduced a multiresolution control method for an APF which is controlled by digital signal processor to meet the requirements for reducing the real-time computational. Morales, Somolinos, Moron, and Garcia (2013) presented a robust controller for a Buck converter based on a state space feedback control system. However, in Braiek et al. (2005), Komucugil and Kukrer (2006), Rahmani et al. (2010), Matas et al. (2008), Montero et al. (2007), Valdez et al. (2009), Hu et al. (2012), and Morales et al. (2013), these control strategies have a common drawback concerning the global stability of the closed-loop system. In Shyu et al. (2008) and Marconi et al. (2007), although the authors solve the stability problem, supply voltage is assumed sinusoidal,while in reality, the utility voltage available at the downstream end is nonsinusoidal due to the harmonic load currents.

Fuzzy control has achieved many practical successes in industrial processes and many other fields. Wang (1994) demonstrated that the fuzzy system can approximate an arbitrary function of a certain set of functions with arbitrary accuracy. Guo and Woo (2004) developed an adaptive fuzzy sliding mode controller for robot manipulator. Tseng and Chen (2009) proposed a fuzzy controller based on fuzzy observer to solve the nonlinear l_∞ – gain control problems. Kim and Kwak (2010) developed an adaptive

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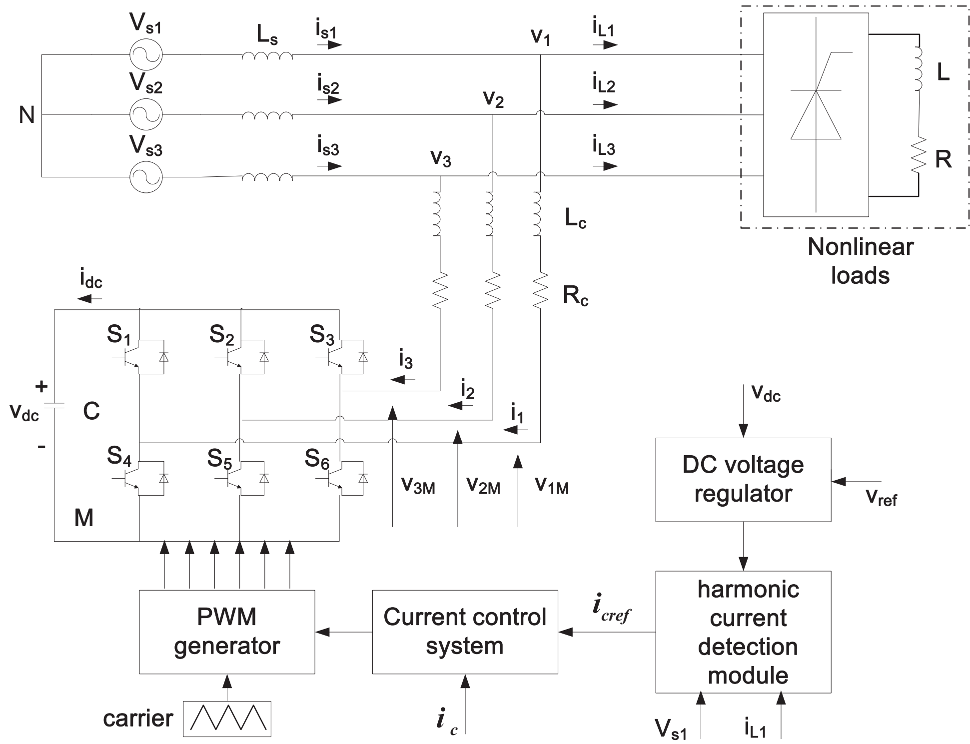

Fig. 1. Block diagram for APF.

neuro-fuzzy method using quantum mechanics based on T-S-K models. Lin and Li (2012) proposed an intelligent trajectory tracking control system of adaptive wavelet fuzzy theory for voice coil motors. Tong, Li, Li, and Liu (2011) showed an adaptive fuzzy backstepping dynamic surface control for nonlinear systems. Fuzzy control researches have been investigated for APF system in recent years. Bhende, Mishra, and Jain (2006) proposed the application of TS-fuzzy-controller for three-phase SAPF. Singh, Singh, and Mitra (2007) developed a fuzzy logic control system based on robust control for APF to minimize the harmonics. Kumar and Mahajan (2009) compared three soft computing control techniques for tracking reference current of APF. However, these fuzzy control strategies have no systematic stability analysis. Lu and Xia (2008) proposed a simple adaptive fuzzy controller for a single-phase SAPF but the adaptive parameters cannot be insured to be stable. Fei and Hou (2012a) developed an adaptive fuzzy system with supervisory controller for APF and ensured the stability of the close-loop system.

Backstepping (Krstic, Kanellakopoulos, & Kokotovic 1995; Chen, 1996; Zhou and Wen, 2008; Fei, Hou, Xue, & Hua 2014) is similarly a recursive Lyapunov-based design procedure which breaks a design problem for the full system into a sequence of design problems for lower order systems. Nevertheless, Backstepping design has two advantages over sliding mode control: one is that the matching condition appeared in the design of sliding mode control can be relaxed for a class of systems satisfying the so called strict feedback form; the other is that backstepping designs can avoid cancelation of useful nonlinearities. The idea of backstepping is to design a controller recursively by considering some of the state variables as “virtual controls” and designing intermediate control laws. Backstepping can achieve the goals of stabilization and tracking. However, so far, adaptive backstepping method has not been employed to eliminate harmonics of active power filter. Fuzzy control is a kind of learning-based control and has strong reasoning ability so that it can be combined with backstepping method to enhance the performance of active power filter. On the basis of an adaptive fuzzy controller proposed in Fei and Hou (2012b), Fei and Hou (2013) presented an adaptive fuzzy sliding controller for APF to ensure robust high-precision control performance. However, as mentioned above, sliding mode control has some drawbacks which backstepping control can overcome. So our work will explore an adaptive fuzzy backstepping control in active power filter.

In this paper, a Lyapunov-based adaptive fuzzy logic controller is applied to approximate the unknown nonlinear functions in APF dynamic systems for the fact that conventional linear controller cannot realize a desired dynamic behavior. Adaptive fuzzy control strategy is utilized to ensure real-time tracking of reference current and strengthen the system robustness. Moreover, adaptive fuzzy control based on backstepping strategy is proposed to improve the current tracking performance and guarantee the Lyapunov stability of the close-loop system. The motivation of the study regarding adaptive fuzzy backstepping control for APF can be emphasized as:

1. The proposed adaptive fuzzy backstepping control strategy need not build accurate mathematical model of APF, which is a common assumption in conventional control methods. So the proposed control overcomes the drawbacks of being difficult to obtain accurate system dynamics and not giving satisfactory performance under parameter variations in the existing control strategies. A compensation control is added into the Lyapunov-based adaptive fuzzy control scheme so that the nonzero problem of the fuzzy approximation errors can be eliminated, thus the asymptotic stability of closed-loop system can be guaranteed.
2. Backstepping control is applied to a three-phase active power filter, and few works exploited this control technique in active power filter before. This control technique is implemented through adaptive fuzzy control to avoid building accurate mathematical model of APF. This makes the control law design