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Robust predictive dual-loop control method based on Lyapunov function stability and energy equilibrium though double-core processors for active power filter

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ABSTRACT

In this paper, a robust predictive dual-loop control method based on Lyapunov function stability and energy equilibrium for active power filter (APF) is proposed to improve the anti-interference performance and self-adaptive capability of system. The proposed control method mainly includes robust predictive current control based on Lyapunov function stability (RPCC-LFS) in the inner current loop and energy equilibrium proportional-integrator (PI) control in the outer dc-link voltage loop. The RPCC-LFS is proposed to enhance self-adaptive capability when the output filter inductors vary, speed up the dynamic response, and improve the tracking accuracy when the loads fluctuate. The energy equilibrium PI controller is proposed to maintain the dc-link voltage stable and suppress the transient impulse. The stability and dynamic response of the proposed control system are analyzed in detail, and the proper control parameters are selected. A specific hardware and software design program based on double-core processors DSP + FPGA is thoroughly given out. Finally, the comparative simulations and experiments verified the validity of the proposed method.

1. Introduction

With the increasing of plenty of nonlinear loads injected into the grid, it is necessary to compensate the harmonic current and reactive power in order to improve power quality and system stability. Active power filter (APF) is used to compensate the harmonic current of the local loads, which had been developed in recent years [1–11].

The voltage and current dual-loop control strategy for APF has been extensively investigated and reported in the previous literatures. The outer voltage loop is usually used to regulate dc-link voltage, and the inner current loop is used to control the grid current of APF [12]. To compensate the harmonic current, many current control methods were proposed, and the corresponding response speed and system stability had also been analyzed [12–14]. In [15], a comprehensive control method is even presented to solve the harmonic compensation under the distorted grid voltage.

In addition, the loads fluctuation of power system could also affect the dynamic response and system stability. To improve the system stability, a novel control strategy based on Lyapunov function stability (LFS) analysis was presented to achieve a globally stable operation without decoupling loop for converters [16–19]. In [17], a Lyapunov-function-based control strategy based on finite control set (FCS) model is proposed to control the load currents of three-phase voltage source inverter (VSI), and a control law based on the Lyapunov stability theory makes the closed-loop system possess a better performance for inverters [16,18]. Owe to predicting variables one and two sample-instants advance, the predictive control method enhanced the system robustness against the loads or dc-link voltage variations [20–24]. In [20], an improved predictive current controller for APF was presented to compensate the delays derived from the digital processors. And Ref. [22] presented a model predictive control to minimize total harmonic distortion (THD) of the output current for APF. The predictive current loop was presented for harmonic filtering control to get a rapid response and low switching frequency [24]. However, the output filter inductors of APF will tend to be saturated with the increasing of the output current. Since the output filter inductance L cannot be accurately measured, these control methods are difficult to achieve an adequate dynamic performance and necessary to further improve the system self-adaptive capability.

As we all known, the traditional PI controller is widely used in the industrial applications due to its simplicity and reliability [25–27]. Ref. [25] adopts traditional PI controller to regulate

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Nomenclature

$u_{sx(x=a,b,c)}$	grid voltage (V)	$ixp*$	output reference value of PI controller (A)
$i_{s\ x(x=a,b,c)}$	grid current (A)	id	output current of d-axis (A)
$i_{cx(x=a,b,c)}$	output current of APF (A)	iq	output current of q-axis (A)
i_L	load current(A)	ω	fundamental angular frequency (rad/s)
R	output resistor(Ω)	sx	duty cycle of each phase bridge arm
L	output filter inductor (mH)	T	switching/sampling period (s)
R_L	load resistor(Ω)	ton	on-time of each period (s)
L_L	load inductor (mH)	kp	proportional coefficient of PI controller
u_{dc}	dc-link voltage (V)	ki	integral coefficient of PI controller
u_{dc}^*	the reference dc-link voltage (V)	α	coefficient of Lyapunov function controller
$i_{xh(x=a,b,c)}$	the reference harmonic current (A)	h	feedback coefficient of output current error
$i_{olx(x=a,b,c)}$	ideal output current under open-loop condition of APF (A)	ts	dynamic response time of charging for u_{dc} (s)

dc-link voltage. However, in practice, a traditional PI controller may not be robust enough due to the sudden variation of the load power or the grid current. Ref. [26] has presented two fuzzy PI controllers to improve the immunity capability of direct output voltage strategy for STATCOM. Simultaneously, the dynamic performance and transient response can be easily affected by the local load fluctuation and transient impulse. However, how to improve the transient stability and robustness of dc-link voltage for APF is less.

In this paper, a robust predictive dual-loop control method based on Lyapunov function stability and energy equilibrium is proposed to improve the anti-interference performance and self-adaptive capability of system for APF with the fluctuation of loads and the variation of output filter inductors. The proposed control method mainly includes RPCC-LFS in the inner current loop and energy equilibrium PI controller in the outer dc-link voltage loop. RPCC-LFS is proposed to enhance the self-adaptive capability with the variation of the output filter inductors, accelerate the dynamic response, and improve the current tracking accuracy when the loads fluctuate. The energy equilibrium PI controller is proposed to maintain the dc-link voltage stable and suppress the transient impulse. The proposed control method will be implemented through double-core processors DSP + FPGA. The remainder of this paper is organized as follows: the APF topology with double-core processors and the principle of the proposed control method are presented in Section 2. The dynamic performance of the proposed method is analyzed in Section 3. A specific double-core processors platform is carried out in Section 4. Finally, the comparative simulation and experimental results between energy equilibrium PI controller and traditional PI controller in the dc-link voltage outer loop, among RPCC-LFS and other typical control methods in the inner current loop, are provided for verifying the feasibility and effectiveness of the proposed control method in Section 5, and some conclusion are given out in Section 6.

2. APF topology and proposed control method

2.1. Overall control structure of APF

The configuration of the global control system with double-core processors for APF is shown in Fig. 1, where APF operates as a VSI, and L and R are the output filter inductance and resistance respectively. The load is a three-phase diode rectifier. The double-core processors combine digital signal processor (DSP) with field programmable gate array (FPGA). And the electronic processors communicate with the terminal interactive system.

2.2. Principle of the proposed control method

The structure of the proposed control method is shown in Fig. 2, which is composed of two parts:

(1) The ***outer loop control*** based on the proposed energy equilibrium PI controller to remain dc-link voltage steady and suppress the transient impulse**.**
(2) The ***inner loop control*** based on the proposed RPCC-LFS to enhance the self-adaptive capability and the dynamic response in case of the output filter inductor variation.

2.2.1. DC-link voltage control method based on energy equilibrium

The voltage error $\Delta u = u_{dc}^* - u_{dc}$ between the dc-link reference voltage u_{dc}^* and dc-link capacitor measured voltage u_{dc} is the input of the PI controller. The output of the PI controller Δe represents the total active current required to maintain u_{dc} at a constant value, and can be expressed as follows:

$$\Delta e = k_p(u_{dc}^* - u_{dc}) + k_i \int (u_{dc}^* - u_{dc})dt \tag{1}$$

where the parameters k_i and k_p are the proportional coefficient and integral coefficient respectively. And the three-phase active currents reference can be obtained by multiplying with three-phase synchronous sinusoidal signals $\sin\omega t$, $\sin(\omega t - 2\pi/3)$ and $\sin(\omega t + 2\pi/3)$. To improve the robustness and dynamic performance, an energy equilibrium PI control method has been proposed to accurately regulate the dc-link voltage.

Ignoring the twice fundamental-frequency ripple of dc-link voltage, the energy equilibrium equation between ac side and dc side can be expressed as

$$\sum_{i=a,b,c} u_{si}(t)i_{ci}(t) - R\sum_{i=a,b,c} i_{ci}^2(t) - \frac{1}{2}L\frac{d}{dt}\sum_{i=a,b,c} i_{ci}^2(t) = Cu_{dc}(t)\frac{du_{dc}(t)}{dt} \tag{2}$$

Assuming that three-phase system is symmetrical, according to the instantaneous reactive power theory, the total three-phase active power of APF system can be obtained as follows:

$$\sum_{i=a,b,c} u_{si}(t)i_{ci}(t) = 3UI_p(t) \tag{3}$$

where U is root-mean-square (RMS) value of the three-phase voltage, and $I_p(t)$ is RMS value of the three-phase active current.

Since the fundamental frequency component of the output current can cause the dc-link voltage fluctuation, the power loss caused by R and L can be equivalent as follows: