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Design and implementation of high performance direct power control of three-phase PWM rectifier, via fuzzy and PI controller for output voltage regulation

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ABSTRACT

This paper proposes direct power control (DPC) for three-phase PWM rectifiers using a new switching table, without line voltage sensors. The instantaneous active and reactive powers, directly controlled by selecting the optimum state of the converter, are used as the PWM control variables instead of the phase line currents being used. The main goal of the control system is to maintain the dc-bus voltage at the required level, while input currents drawn from the power supply should be sinusoidal and in phase with respective phase voltages to satisfy the unity power factor (UPF) operation. Conventional PI and a designed fuzzy logic-based controller, in the dc-bus voltage control loop, have been used to provide active power command. A dSPACE based experimental system was developed to verify the validity of the proposed DPC. The steady-state, and dynamic results illustrating the operation and performance of the proposed control scheme are presented. As a result, it was confirmed that the novel DPC is much better than the classical one. Line currents very close to sinusoidal waveforms (THD < 2%) and good regulation of dc-bus voltage are achieved using PI or fuzzy controller. Moreover, fuzzy logic controller gives excellent performance in transient state, a good rejection of impact load disturbance, and a good robustness.

1. Introduction

Most three-phase rectifiers, extensively employed in industrial fields and consumer products, use a diode bridge circuit and a bulk storage capacitor. This has the advantages of being simple, robust, and low in cost. However, a diode rectifier results in only unidirectional power flow, low power factor, and high level of harmonic input currents. Apart from application of active and passive filters, the best solution is in using pulse width modulated (PWM) rectifiers. Research interest in three-phase PWM rectifiers has grown rapidly over the last few years due to some of their important advantages, such as power regeneration capabilities, control of dc-bus voltage over a wide range, and low harmonic distortion of input currents. Since the converter has abilities to control the input currents in sinusoidal waveforms, unity power factor (UPF) operation can be easily performed by regulating the currents in phase with the power-source voltages.

Various control strategies have been proposed in recent works on this type of PWM rectifier. It can be classified for its use of current loop controllers or active/reactive power controllers. The well-known method of indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector. It is called voltage-oriented control (VOC) [1–5]. VOC guarantees high dynamics and static performance via internal current control loops. However, the final configuration and performance of the VOC system largely depends on the quality of the applied current control strategy. Over the last few years, an interesting emerging control technique has been direct power control (DPC), developed analogously with the well-known direct torque control (DTC) used for adjustable speed drives [5–12]. In DPC schemes, there are no internal current loops and the converter switching states are appropriately selected by a switching table based on the instantaneous errors, between the commanded and estimated values of instantaneous active and reactive power, and the power-source voltage vector position [6] or virtual-flux vector position [8].

This paper proposes a novel direct power control (DPC) for a three-phase PWM rectifier, which makes it possible to achieve unity power factor operation by directly controlling its instantaneous active and reactive power without any power-source voltage sensors. The proposed technique has two features. One is a method for synthesizing a new switching table, different from the one

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found in the control of ac machines and used in [6] and in [8], is proposed. This new switching table is synthesized by analyzing the instantaneous active and reactive power correction. The other is a fuzzy logic controller, in the dc-bus voltage control loop, developed to provide active power command. To achieve unity power factor operation, the reactive power command is set to zero. This controller based on fuzzy logic allows more flexibility and better dynamic response. Finally, the proposed DPC is simulated and implemented for both conventional PI controller and fuzzy controller. It is shown via simulation and experimental results that the proposed DPC has high performance compared to the classical one. The line currents are very close to sinusoidal waveforms, a good regulation of the dc-bus voltage is obtained, and UPF operation is achieved. Moreover, the controller based on fuzzy logic has excellent performance in transient and steady states, a good robustness, a good dynamic behaviour for dc-bus voltage regulation, and a good rejection of impact of load disturbance.

2. Principles of DPC

2.1. System configuration

DPC is based on the instantaneous active and reactive power control loops. In DPC there are no internal current control loops. The converter switching states are selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power. Fig. 1 shows the configuration of the direct instantaneous active and reactive power control for three-phase PWM rectifier in which the symbols are as follows:

e_a, e_b,e_c three-phase power-source voltages; v_a, v_b, v_c ac terminal voltages of the PWM rectifier;
i_a, i_b, i_c three-phase line currents; S_a, S_b, S_c switching states of the converter;
L, R inductance and resistance of reactors; C, R_L dc-link capacitor and load resistance.

The controller features relay control of the active and reactive power by using hysteresis comparators and a switching table. In this configuration, the dc-bus voltage is regulated by adjusting the active power, and the unity power factor operation is achieved by controlling the reactive power to be zero.

As shown in Fig. 1, the active power command, P^*, is provided from a dc-bus voltage controller block. The reactive power command, q^*, is directly given from the outside of the controller. Errors between the commands and the estimated feedback power are input to the hysteresis comparators and digitized to the signals S_p and S_q. where:

$$S_p = 1 \quad \text{if } p^* - \hat{p} \geqslant h_p, \quad S_p = 0 \quad \text{if } p^* - \hat{p} \leqslant -h_p$$
$$S_q = 1 \quad \text{if } q^* - \hat{q} \geqslant h_q, \quad S_q = 0 \quad \text{if } q^* - \hat{q} \leqslant -h_q$$

Also, the phase of the power-source voltage vector is converted to the digitized signal θ_n. For this purpose, the stationary coordinates are divided into twelve sectors, as shown in Fig. 2, and the sectors can be numerically expressed as:

$$(n-2)\frac{\pi}{6} \leqslant \theta_n \leqslant (n-1)\frac{\pi}{6} \quad n = 1, 2, \ldots, 12. \tag{1}$$

The digitized error signals S_p and S_q and digitized voltage phase θ_n are input to the switching table in which every switching state, S_a, S_b, and S_c, of the converter is stored. By using this switching table, the optimum switching state of the converter can be selected uniquely in every specific moment according to the combination of the input signals.

2.2. Switching table synthesizing

In the stationary reference frame α–β and for a balanced three-phase system, the line currents equation can be presented as

$$\begin{aligned} \frac{di_\alpha}{dt} &= \frac{1}{L}(e_\alpha - v_\alpha - R \cdot i_\alpha) \\ \frac{di_\beta}{dt} &= \frac{1}{L}(e_\beta - v_\beta - R \cdot i_\beta) \end{aligned} \tag{2}$$

From (2), line current vector $[i_\alpha, i_\beta]^T$ can be controlled by selecting the proper rectifier voltage vector. The change in line current depends on the actual power-source voltage vector $e_{\alpha\beta}$, on the selected rectifier voltage vector $v_{\alpha\beta}$, and in less measure on the actual line current. The parameter R can be practically neglected and a discrete first order approximation of (2) can be adopted. So the change in line current for the next control period is given by

$$\begin{aligned} \Delta i_\alpha &= i_\alpha(k+1) - i_\alpha(k) = \frac{T_s}{L}(e_\alpha(k) - v_\alpha(k)) \\ \Delta i_\beta &= i_\beta(k+1) - i_\beta(k) = \frac{T_s}{L}(e_\beta(k) - v_\beta(k)) \end{aligned} \tag{3}$$

In the stationary reference frame α–β the instantaneous active and reactive power are defined as follows: [13,14]

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ e_\beta & -e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4}$$

As first approximation, and if the switching frequency is high enough, the change in power-source voltage can be neglected. The change in the active and reactive power can be estimated for the next control cycle as follows:

$$\begin{cases} \Delta P = e_\alpha(k) \cdot \Delta i_\alpha + e_\beta(k) \cdot \Delta i_\beta \\ \Delta q = e_\beta(k) \cdot \Delta i_\alpha - e_\alpha(k) \cdot \Delta i_\beta \end{cases} \tag{5}$$

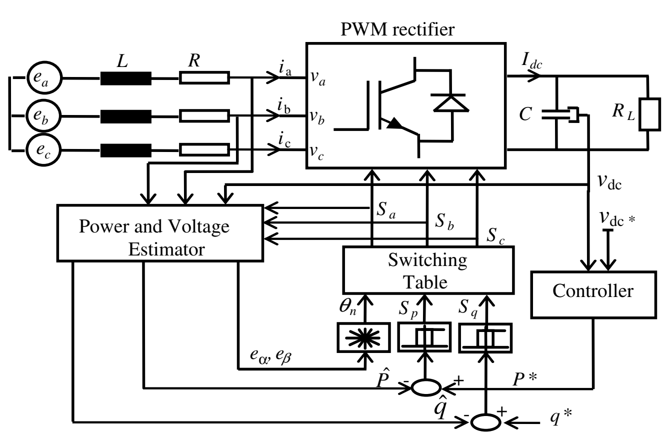

Fig. 1. Configuration of DPC for three-phase PWM rectifier.

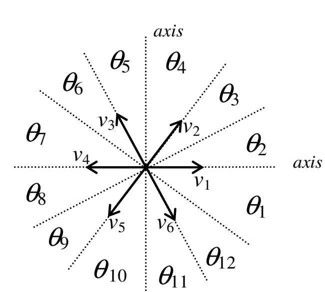

Fig. 2. Twelve sectors on stationary coordinates to specify voltage phase and rectifier voltage vectors.