Energy Conversion and Management 51 (2010) 947–954

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

High performance direct instantaneous power control of PWM rectifiers

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ARTICLE INFO

Article history:
Received 21 April 2009
Accepted 27 November 2009
Available online 6 January 2010

Keywords:
Direct power control
Three-phase PWM converter
Instantaneous active and reactive power
Parameter sensitivity

ABSTRACT

This paper presents a new direct instantaneous power control (DPC) strategy for active rectifiers. In this novel scheme the PWM modulator has been utilized instead of the hysteresis comparators and switching table. The required converter voltage in each sampling period is directly calculated based on the reference and measured values of powers, system parameters, and the measured voltage of the AC source through simple equations which are wisely compensated for variations of the grid voltage during a sampling period. Then, the PWM generator generates the switching pulses for the voltage source converter. It is shown that the proposed DPC–PWM exhibits several features, such as a simple algorithm, constant switching frequency, robust to sampling frequency changes, robust to inductance values mismatch, and particularly it provides low sampling frequency. Extensive simulation and experimental results have proven the excellent performance and verify the validity and effectiveness of the proposed instantaneous power control scheme.

1. Introduction

The increasing power demand in most of the consumer centers has forced the planning engineers to look for new solutions to improve the quality of electrical utility systems. Conventional applications of VSC such as AC and DC drives, AC and DC power supplies, active filters, electrolyze systems, and electric furnaces require controlling the active power or accurate control of DC link voltage at set value. DC link voltage control (usually through PI regulator) leads to active power control. As power electronic systems are extensively used, not only in industrial applications, but also in consumer products, several problems with regard to their diode rectifiers have arisen in recent years. One of the problems is a low input power factor, and another problem is caused by harmonics in input currents. Research interest in three-phase PWM rectifiers has grown rapidly over the past few years due to some of their important advantages, such as power regeneration capabilities, control of DC link voltage, low harmonic distortion of input currents, bidirectional control of active and reactive powers, small DC link capacitor, and high power factor (usually, near unity) [1]. Various control strategies have been proposed in recent works on this type of rectifiers. A well-known method of indirect active and reactive power control is based on the current vector orientation with respect to the line voltage vector called voltage-oriented control or VOC. The VOC guarantees high dynamics and static performance via internal current control loops. The scheme decouples the converter currents into active and reactive power components. Control of the active and reactive powers is then achieved by controlling the decoupled converter currents using current controllers. One main drawback of such a system is that the performance is highly dependent on the applied current control strategy and the connected AC network conditions [1]. Another control strategy called direct power control (DPC) is based on the instantaneous active and reactive power control. In DPC, there are no internal current control loops and no PWM modulator block, because the converter switching states are appropriately selected by a look-up table based on the instantaneous errors between the commanded and measured values of the active and reactive powers. Compared to the VOC, there is a simpler algorithm, no current control loops, no coordinate transformation and separate PWM voltage modulator, no need for decoupling between the control of the active and reactive components, and better static and dynamics performance. However, among the well-known disadvantages of the DPC scheme are [2–18]: variable switching frequency (difficulties of converter and filter design); high sampling frequency needed for digital implementation of hysteresis comparators; large inductance needed between the AC source and the converter; and some problems due to the high gain of the hysteresis controllers.

In this research work a novel method for direct power control of three-phase pulse-width-modulated converters is presented. In this method hysteresis comparators and switching table are replaced by PWM voltage modulator. The required converter voltage in each sampling period is directly calculated based on only

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0196-8904/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2009.11.034

reference and measured values of active and reactive powers, system parameters, and the measured voltage of the AC source. Then, the PWM generator synthesizes the reference voltage and generates the switching pulses for the voltage source converter. Compared to the VOC, and conventional DPC there is a simpler algorithm, no current control loops, there is no need for decoupling between the control of active and reactive components, and finally, no hysteresis controllers are required. Simulation and experimental results show that the proposed method is more robust to sampling frequency variations than the conventional method do. Also parameter value mismatch has negligible effect on power tracking performance. The proposed strategy besides having the conventional switching table based DPC method advantages, offers many unique features such as:

- fixed and low switching frequency;
- low sampling frequency needed for digital implementation;
- simple and easy for real time implementation;
- no hysteresis controller and linear PI controller;
- small inductance needed between the AC source and the converter;
- robust to sampling frequency variations; and
- inductance values mismatch has negligible effect on active and reactive power tracking performance.

2. Principles of classical DPC

Fig. 1 shows the configuration of the direct instantaneous active and reactive power controller for the PWM converter. Direct power control is based on the instantaneous active and reactive power control loops [2,3]. With DPC there are no internal current control loops and no PWM modulator block, because the converter switching states, in each sampling period, are selected from a switching table based on the instantaneous errors between the commanded and measured or estimated values of active and reactive powers, and the angular position of the source voltage vector. In this configuration, usually, the DC link voltage is regulated by controlling the active power, and the unity power factor operation is achieved by controlling the reactive power to be zero. The DPC idea has been proposed by Ohnishi [2]. For the first time he used the instantaneous active and reactive power values as control variables instead of instantaneous three phase line currents ever used. He established first a proportional relationship between the instantaneous power values and the currents expressed in the rotational reference frame which only holds for the balanced sinusoidal operation. Since the converter voltage is related to the time derivatives of the line currents, so there is a relationship between the injected converter voltage and the time derivatives of the instantaneous active and reactive powers. Thus, the reference voltage for the PWM block is proposed in such a way that the sign of these derivatives opposes the sign of the errors in the active and reactive powers. For this purpose, hysteresis controllers are utilized which are simple and have a high gain. Because this method still needs a PWM block, so it cannot yet be considered as direct, however, the principle of DPC is based on the Ohnishi's idea. The term "Direct Power Control" or DPC for the first time was used by Noguchi et al. for the control scheme depicted in Fig. 1 [3]. This method is based on selecting a voltage vector from a look-up table, Table 1, according to the errors of active and reactive powers as well as the angular position of the source voltage vector. The entries of the table which hereafter named the switching table was determined in order to minimize the errors between the commanded and measured or estimated powers in each sampling period. Also to achieve a better performance, they proposed to divide the vector space into twelve sectors and then determine the position of the source voltage vector accordingly.

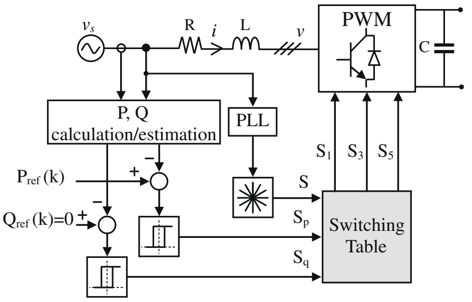

Fig. 1. Basic configuration of DPC for three-phase PWM converters [3].

The most significant drawback of the DPC is the variable switching frequency which mainly depends on the sampling frequency, the switching table structure, system parameters, reference values of the active and reactive powers, hysteresis bands, and finally the converter switching status. This variable switching frequency will produce a broadband harmonic spectrum in the AC line currents. Because of these harmonics the design of filters will be difficult. On the other hand, DPC controllers are hysteresis type. These controllers cannot guarantee the perfect tracking of a time varying signal, unless arbitrarily high sampling/switching frequencies are used. Besides, due to their high gain, they are too much sensitive to current ripples which may disturb the control. So, in order to achieve an acceptable performance, large values for the sampling frequency and the filter inductance should be selected to attenuate the current ripples. Large inductance value leads to increased cost, dimensions, weight, and losses, and also reduces the system dynamics. Above mentioned problems can be eliminated by avoiding the hysteresis controllers and also introducing a space vector modulator (SVM) in control strategy [4–8]. Moreover, the line voltage sensors can be replaced by virtual flux (VF) estimator, which introduces technical and economical advantages to the system such as: simplification, reliability, galvanic isolation, and cost reduction. In this method hysteresis comparators and switching table are replaced by linear PI controllers and SVM. The main drawback for such a system is that the performance is highly dependent on the tuning of the PI controller. Rodriguez et al. proposed a new strategy that eliminates the hysteresis controllers and switching table [9,10]. A predictive DPC is presented in their work for the control of the AC/DC/AC converter. In the proposed control strategy, the finite possible switching states of the AC/DC/AC are considered, the effect of each one on the load current and input power is evaluated, and the switching state that minimizes a quality function is selected and applied during the next sampling period. The quality function evaluates the load current error for the inverter, and the input active and reactive power error for the rectifier. Restrepo et al. conducted a similar work in which the quality function minimizes the active and reactive power errors [11,12]. Predictive approaches have also been employed in order to overcome the variable switching frequency problem of the DPC strategy [13,14]. Instead of selecting an instantaneous optimal voltage vector, these approaches select an optimal set of concatenated voltage vectors, which is the so-called "voltage-vectors sequence." The control problem is solved by computing the application times of the sequence vectors in such a way that the controlled variables converge toward the reference values along a fixed predefined switching period. In this way, constant switching frequency operation is obtained. Several authors have developed this concept in multilevel converter topologies linked to different kind of machines, but there are few predictive control applications on line-connected VSC systems. They called their proposed method P-DPC. Unfortunately, these methods require complex computation intensive and may not be viable in industrial applications. Also