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Predictive direct power control of three-phase boost rectifier

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Abstract. In this paper, a new control scheme of an active boost rectifier has been presented. Proposed power control method uses a discrete-time model of the converter to predict future behaviour for all possible voltage vectors. The most effective vector is chosen for next sampling period by minimizing a cost function. Presented Predictive Direct Power Control (P-DPC) scheme has been compared with classical Switching Table based Direct Power Control (ST-DPC) method. Laboratory results shows that predictive control in relation to classical ST-DPC method works properly at low sampling frequency and owns better dynamic and steady state performance.

Key words: active rectifier, direct power control, predictive control.

1. Introduction

Most three-phase rectifiers use a diode bridge circuit with a bulk storage capacitor on dc side. This has the advantages of being simple, robust, and low in cost. However, a diode rectifier performs only unidirectional power flow and is characterized by poor power factor and high level of harmonic line currents. This leads to harmonic pollution and additional power losses in distribution system. Therefore, a three-phase active boost rectifier (Fig. 1) is a promise solution for industrial application thanks to important advantages such as:

- Bidirectional power flow;
- Sinusoidal line current with low harmonic distortion;
- Regulation of input power factor to unity;
- Adjustment and stabilization of dc-link voltage;
- Reduced dc filter capacitor size.

Development of control methods for active boost rectifiers was possible thanks to advances in power semiconductor devices and digital signal processors, which allow fast operation and cost reduction. It offers possibilities for implementation of sophisticated control algorithms. Appropriate control can provide both the rectifier performance improvements and reduction of passive components which is very important for high power systems.

Various control strategies have been proposed in recent works on this type of PWM rectifier [1–11]. A well-known method of indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector and is known as voltage-oriented control (VOC) [1,3,9,10]. 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 [2].

Another approach is based on instantaneous direct active and reactive power control, and is called direct power control (DPC) [7,8]. On the basis of hysteresis controllers outputs and position of supply line voltage space vector a proper switching states are selected from switching table (ST) for next sampling period. However, high sampling frequency requirement is a main drawback of the switching table based direct power control (ST-DPC) scheme.

Several predictive algorithms have been proposed for inverter-fed indodion motor control [12,13]. However, the application to control of three-phase boost rectifier is limited [11,14]. This paper presents different approach to control of the rectifier based on predictive algorithm. Behaviour of active and reactive powers is predicted for all possible voltage vectors generated by the rectifier. The switching state which minimizes a cost function is selected for next sampling period. Such predictive direct power control (P-DPC) is different from classical ST-DPC scheme and allows selecting switching states which are not considered in DPC look up table.

2. Mathematical model of rectifier

Model of two level converter is shown in Fig. 1. It includes choke at the input and load at the dc output of the rectifier.

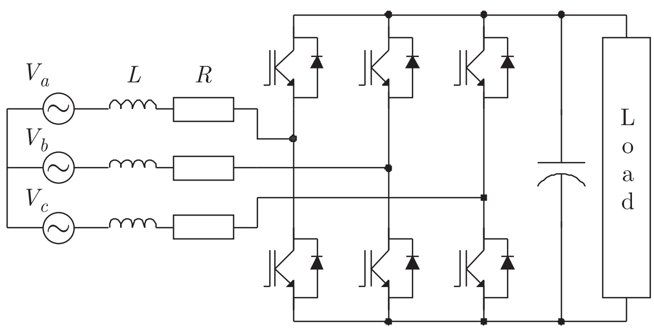

Fig. 1. Rectifier model

Main equation of rectifier can be described in $\alpha\beta$ coordinates as follows:

$$L\frac{d\mathbf{I}_{\alpha\beta}}{dt} = \mathbf{V}_{\mathbf{G}\alpha\beta} - \mathbf{V}_{\mathbf{P}\alpha\beta} - R\mathbf{I}_{\alpha\beta} \qquad (1)$$

Where $\mathbf{I}_{\alpha\beta}$ is the space vector of line current, $\mathbf{V}_{\mathbf{G}\alpha\beta}$ is the space vector of line voltage and $\mathbf{V}_{\mathbf{P}\alpha\beta}$ is the space vector of

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voltage generated by the rectifier, which can be described as:

$$\mathbf{V_{P(n)}} = \begin{cases} \frac{2}{3} U_{DC} e^{j(n-1)\frac{\pi}{3}} & n = 1...6 \\ 0 & n = 0.7 \end{cases} \tag{2}$$

Figure 2 presents six active and two zero voltage vectors generated by the rectifier.

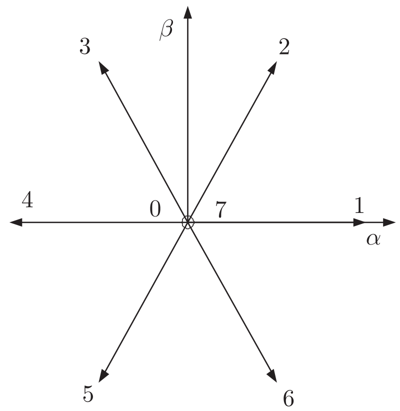

Fig. 2. Possible voltage vectors generated by the rectifier

3. Predictive control strategy

Proposed control method is shown in Fig. 4. Control of the active and reactive powers is made by the predictive controller. The PI controller is used to regulate DC side voltage, and to generate reference value of active power. To obtain unity power factor condition, reference value of reactive power is equal to zero.

After transformation equation (1) into dq coordinates, mathematical model of rectifier is given by equation:

$$\mathbf{V_{Gdq}}(k) = L\frac{d\mathbf{I_{dq}}(k)}{dt} + \mathbf{V_{Pdq}}(k) - j\omega L \mathbf{I_{dq}}(k) \tag{3}$$

Next taking into account commanded and calculated values of active and reactive powers equation (3) can be rearranged to calculate reference value of voltage at the input of rectifier:
In d axis:

$$\begin{aligned} V_{PdC}(k) = V_{Gd}(k) - &\left(\frac{P_C(k)V_{Gd}(k) + Q_C(k)V_{Gq}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \\ \times \left(R + \frac{L}{T_s}\right) + \frac{L}{T_s} &\left(\frac{P(k)V_{Gd}(k) + Q(k)V_{Gq}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \\ -\omega L &\left(\frac{P(k)V_{Gq}(k) - Q(k)V_{Gd}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \end{aligned} \tag{4}$$

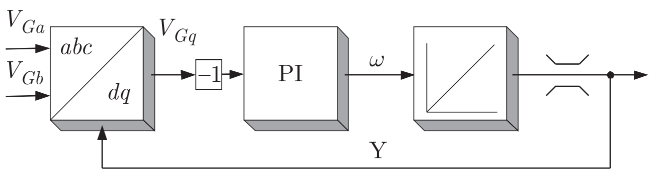

Fig. 3. Block diagram of Digital Phase Locked Loop scheme

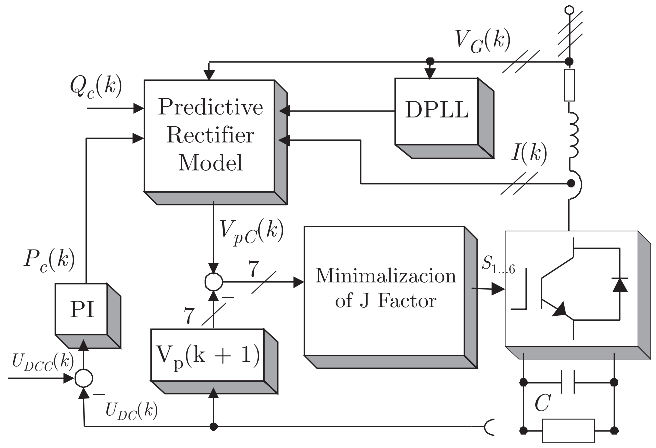

Fig. 4. Block diagram of predictive direct power control (P-DPC) scheme

In q axis:

$$\begin{aligned} V_{PqC}(k) = V_{Gq}(k) - &\left(\frac{P_C(k)V_{Gq}(k) - Q_C(k)V_{Gd}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \\ \times \left(R + \frac{L}{T_s}\right) + \frac{L}{T_s} &\left(\frac{P(k)V_{Gq}(k) - Q(k)V_{Gd}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \\ +\omega L &\left(\frac{P(k)V_{Gd}(k) + Q(k)V_{Gq}(k)}{\left(V_{Gd}^2(k) + V_{Gq}^2(k)\right)} \right) \end{aligned} \tag{5}$$

Thanks to use Digital Phase Locked Loop (DPPL) of Fig. 3, the control system is well synchronized with line voltage space vector and therefore: $V_{Gq}(k) = 0$. For unity power factor condition the command value of reactive power is set to zero. Taking into account these two conditions, equations (4) and (5) can be simplified to:

$$\begin{aligned} V_{PdC}(k) = V_{Gd}(k) - &\frac{P_C(k)}{V_{Gd}(k)}\left(R + \frac{L}{T_s}\right) \\ &+ \frac{L}{T_s}\frac{P(k)}{V_{Gd}(k)} - \omega L \left(\frac{-Q(k)}{V_{Gd}(k)}\right) \end{aligned} \tag{6}$$

$$V_{PqC}(k) = -\frac{L}{T_s}\left(\frac{Q(k)}{V_{Gd}(k)}\right) + \omega L \frac{P(k)}{V_{Gd}(k)} \tag{7}$$

where T_s is time sampling and ω is angular frequency of line voltage.

After that seven possible voltage vectors $\mathbf{V_{Pdq}(k+1)}$ are calculated and predictive controller selects appropriate switching state which minimizes the cost function described as:

$$\begin{aligned} &\mathbf{J}[7] = \\ &|(V_{Pdc}(k) - V_{Pd}(k+1)[7]) + j\,(V_{Pqc}(k) - V_{Pq}(k+1)[7])| \end{aligned} \tag{8}$$

The mathematical model of the system is used to predict future behaviour of rectifier for all possible switching states generated by the converter.

4. Switching table based direct power control

Switching Table based Direct Power Control (ST-DPC) uses line voltage and line current measurement. On the basis of DC side voltage error PI controller generates command value of active power, whereas command value of reactive power is set to zero to achieve unity power factor condition (Fig. 5).

Active and reactive power can be calculated as below:

$$\begin{aligned} p(k) &= 3/2\left(V_{G\alpha}(k)\, i_\alpha(k) + V_{G\beta}(k)\, i_\beta(k)\right) \\ q(k) &= 3/2\left(V_{G\beta}(k)\, i_\alpha(k) - V_{G\alpha}(k)\, i_\beta(k)\right) \end{aligned} \tag{9}$$

Next power errors are delivered to hysteresis controllers, which are constructed:

```
if (p_err > hist) Sp=1;
else if (p_err < -hist) Sp=0;
else if ((p_err < hist) &&
(p_err > -hist)) Sp=Sp_old;
Sp_old=Sp;
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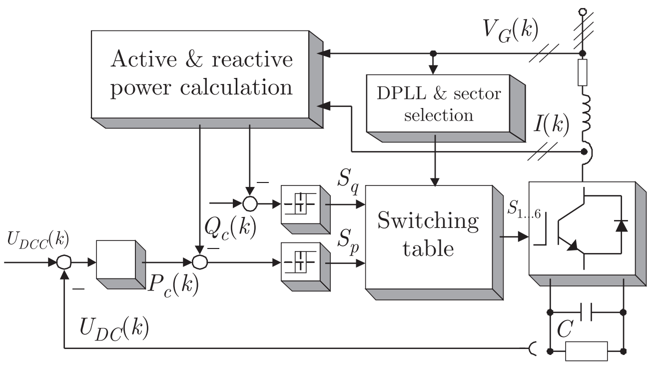

Fig. 5. Block diagram of Switching Table based Direct Power Control (ST-DPC) scheme

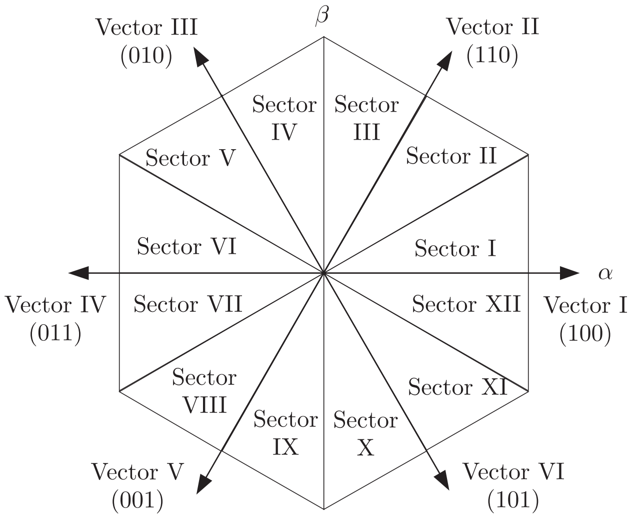

Fig. 6. Voltage plane with 12 sectors

On the basis of controller's outputs and line voltage space vector position Fig. 3, an appropriate voltage vector is selected from switching table. The plain of voltage position is divided into twelve sectors as shown in Fig. 6.

Table 1 summarizes selected voltage vector numbers for all possible combinations of controller's outputs in order to line voltage vector placement.

Table 1
Switching state table

Sp	Sq	Sector											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
0	0	1	2	2	3	3	4	4	5	5	6	6	1
1	0	6	1	1	2	2	3	3	4	4	5	5	6
0	1	2	2	3	3	4	4	5	5	6	6	1	1
1	1	7	7	0	0	7	7	0	0	7	7	0	0

5. Simulation and experimental results

Both control structures have been simulated using Matlab SimPower Toolbox.

Experimental investigation was made on a laboratory setup which consists of input choke, PWM converter VLT 5005 produced by Danfoss Company, control system based on DSpace 1103 board. The main data and parameters are given in Table 2.

Table 2
Main data of simulation and laboratory setup

Line voltage	150 V_{max}
Voltage frequency	50 Hz
Input inductance	10 mH
Resistance of input choke	100 mΩ
DC-link capacitor	470 μF
Sampling frequency	20 kHz

The performance of the P-DPC scheme depends strongly on parameter (mainly inductance) values used in the prediction model given by the equations (6) and (7). Also the change of the load influences the quality of the line current and switching frequency value. The measured results of Fig. 7 (a) and (b) show clearly that this dependency is nonlinear. Even though these monograms are measured for defined parameters of the laboratory set-up, they show a general tendency and can be used for design of such a type of controllers. Thereinafter all measurements and simulations for the P-DPC are made for L = 5 mH in the predictive model.

The performance of presented control system was tested for step change of commanded active power P_C from 750 W to 1.5 kW. Commanded reactive power is equal to zero. Figures 8, 10 and 11 show very good dynamic behaviour of electrical variables. The active power follows the commanded value without any interaction to the reactive power. Line currents are sinusoidal and in phase with line voltage.

Dynamic test shows that predictive P-DPC scheme has faster response than classical ST-DPC, because it may use any vector which minimizes cost function at every sampling period, while classical DPC can use only vectors declared in the look up switching table.

Also Predictive DPC has higher switching frequency and that's why it controls powers better than classical DPC. Figures 9 and 12 show steady state results for both controls under 1.5 kW of load. Table 3 summarizes achieved laboratory results.

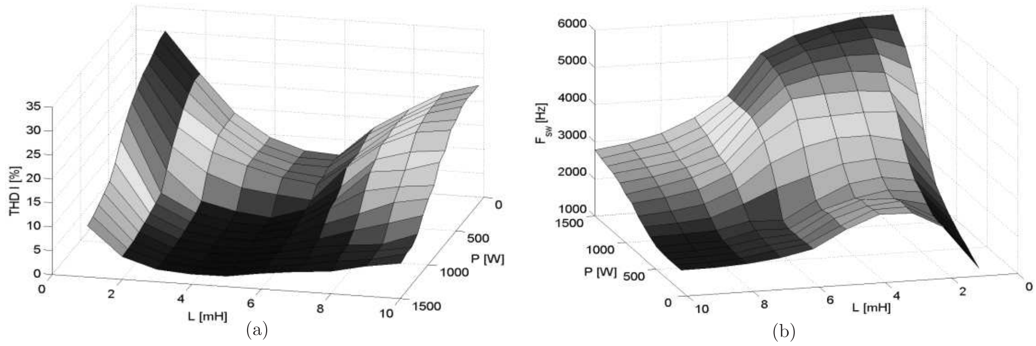

Fig. 7. Measured line current THD factor and converter switching frequency (a) versus inductance L used in prediction model and DC output power (b)

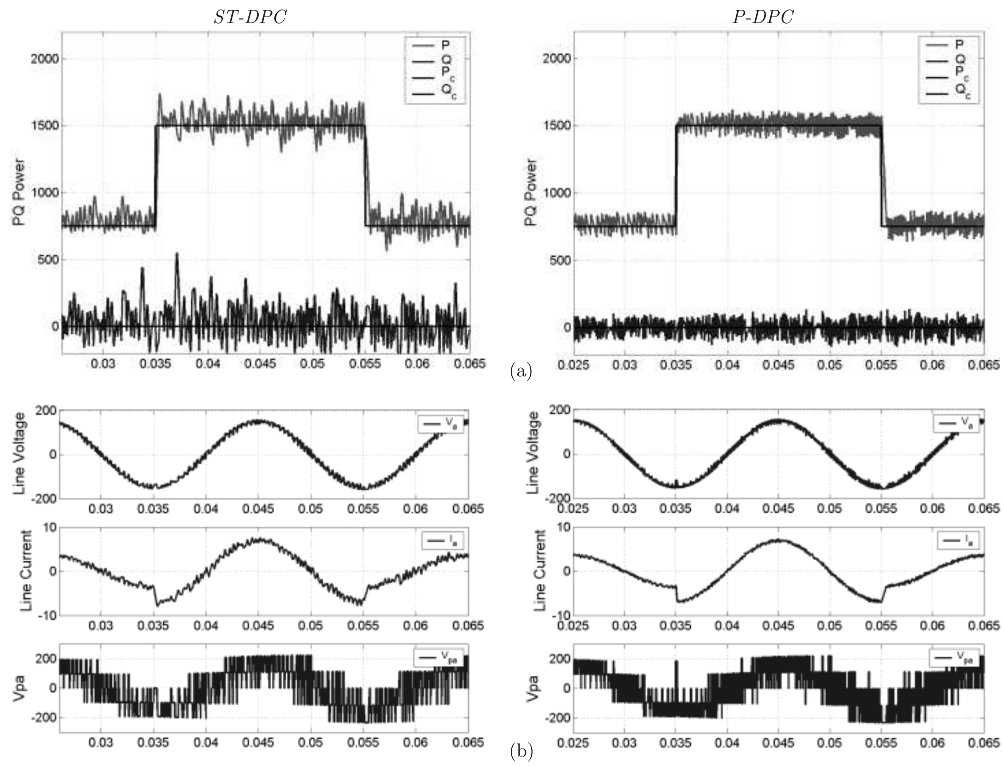

Fig. 8. Simulated tracking performance of active power for command change from 750 W to 1.5 kW and to 750 W (simulation), on the left ST-DPC, on the right P-DPC. From the top: commanded and measured active powers, commanded and measured reactive powers (a), line voltage, line current, voltage on the input of rectifier (b)

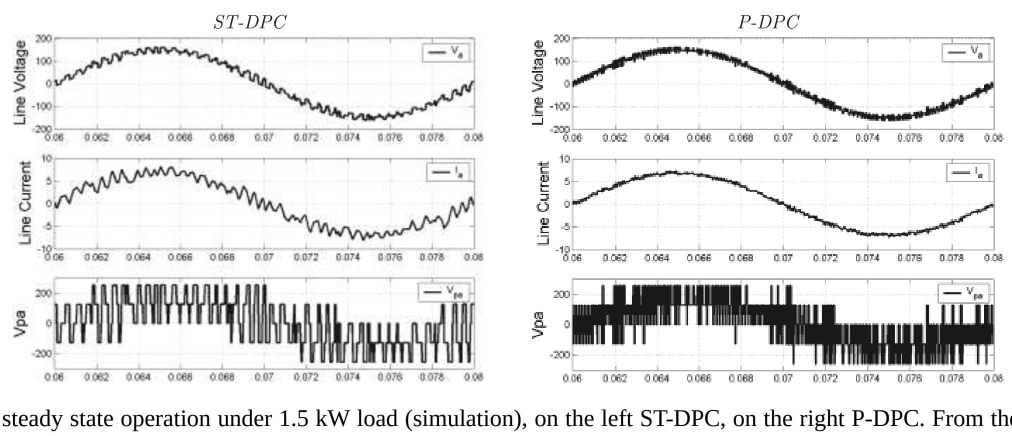

Fig. 9. Simulated steady state operation under 1.5 kW load (simulation), on the left ST-DPC, on the right P-DPC. From the top: line voltage, line current, voltage on the input of rectifier

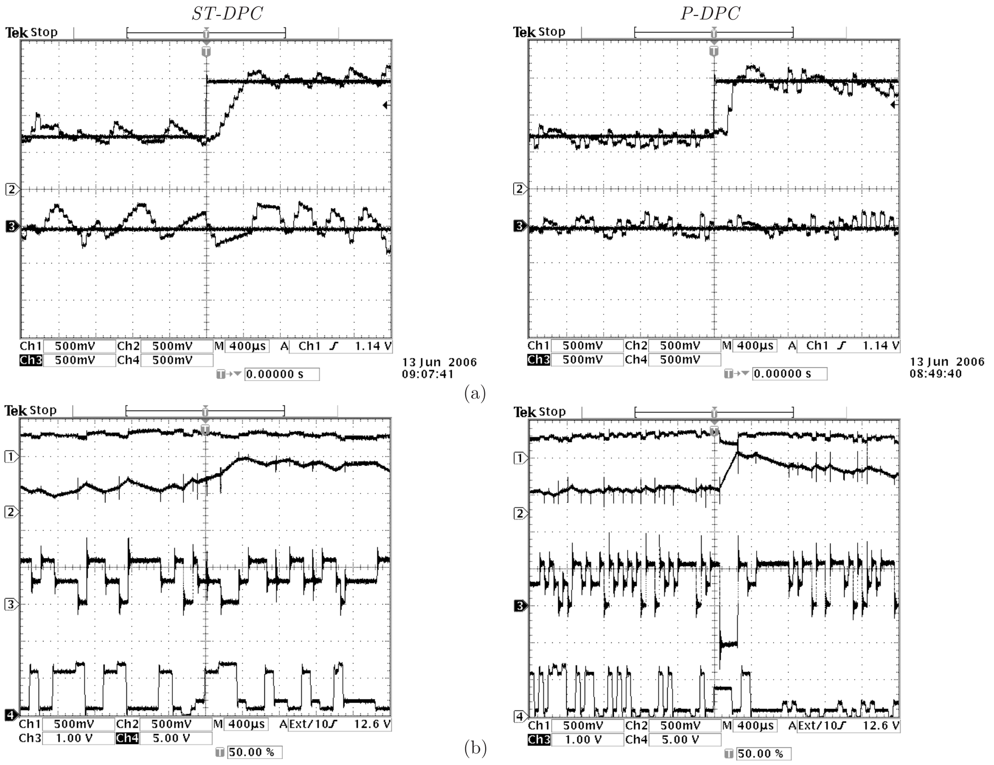

Fig. 10. Experimental tracking performance of active power for command change from 750 W to 1.5 kW, on the left ST-DPC, on the right P-DPC. From the top: commanded and measured active powers, commanded and measured reactive powers (a), line voltage, line current, voltage on the input of rectifier, selected voltage vector (b)

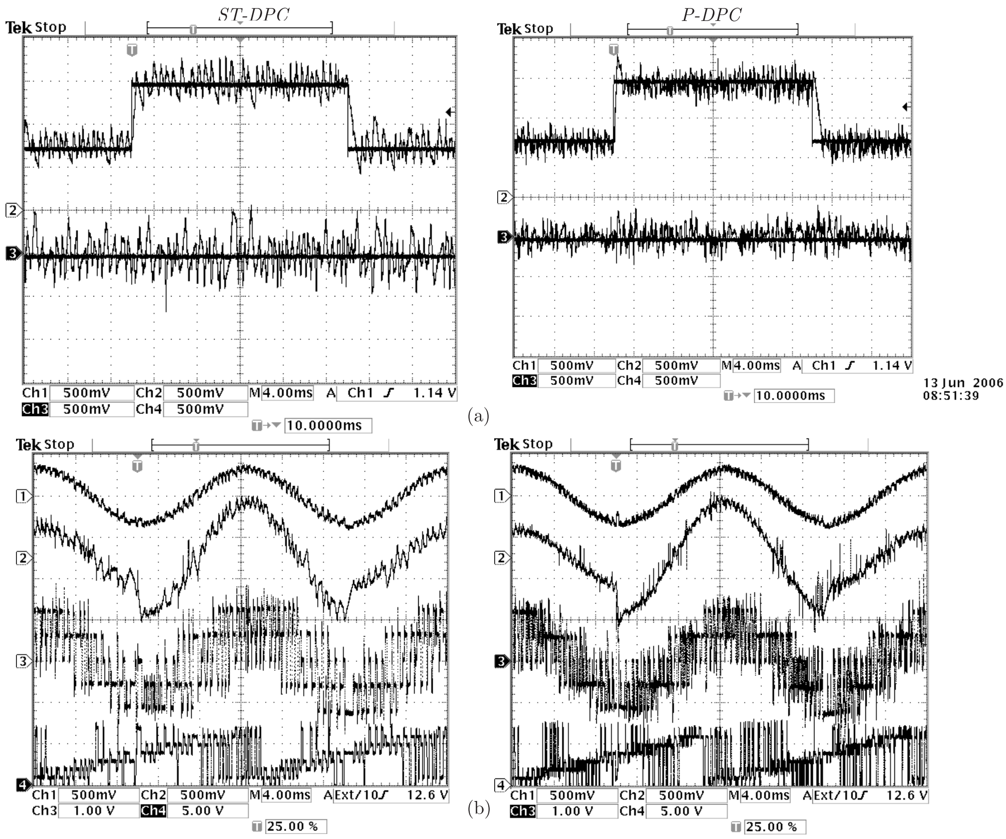

Fig. 11. Experimental tracking performance of active power for command change from 750 W to 1.5 kW and to 750 W, on the left ST-DPC, on the right P-DPC. From the top: commanded and measured active powers, commanded and measured reactive powers (a), line voltage, line current, voltage on the input of rectifier, selected voltage vector (b)

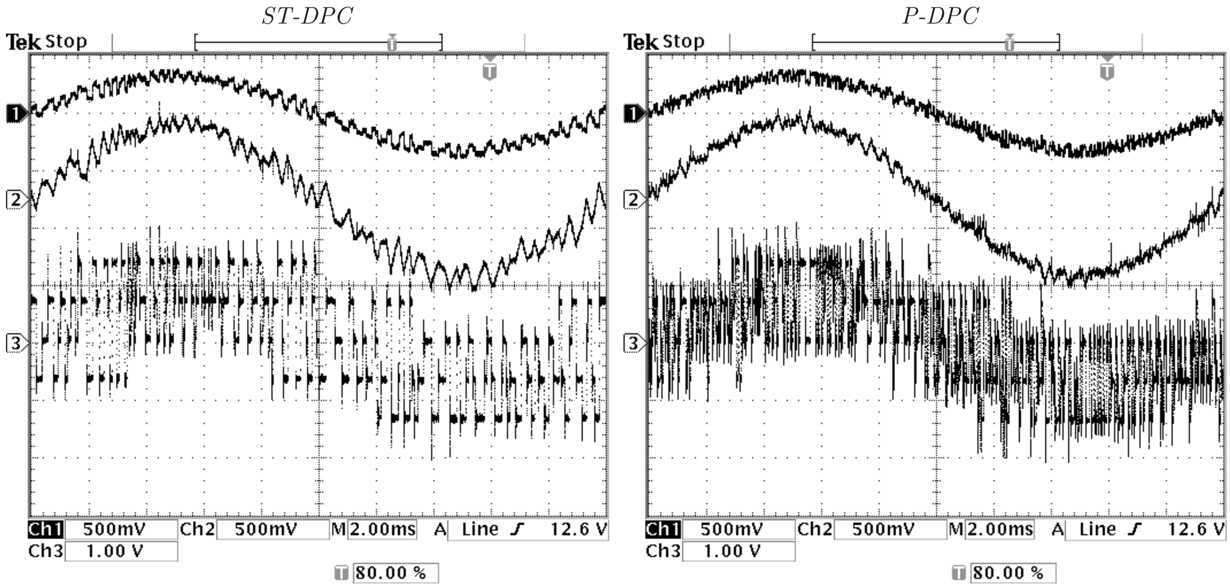

Fig. 12. Experimental steady state operation under 1.5 [kW] load, on the left ST-DPC, on the right P-DPC. From the top: line voltage, line current, voltage on the input of rectifier

Table 3
Laboratory measurements

	ST-DPC	Predictive DPC
Sampling Frequency	20 kHz	20 kHz
Av. Switching Frequency	2.1 kHz	5.5 kHz
Line Voltage THD	4.5%	1.5 %
Line current THD	7%	2%

6. Conclusions

In this paper two different control structures: Predictive Direct Power Control (P-DPC) and Switching Table based Direct Power Control (ST-DPC) have been analyzed for an active rectifier application.

Simulation and experimental results show that presented novel P-DPC method provides sinusoidal line currents in phase with line voltage and very good dynamic of controlled variables. This control algorithm is more complicated than classical ST-DPC; however, it gives lower THD factors of line currents and voltages with 20 kHz of sampling frequency. To achieve similar results ST-DPC scheme requires at least three times higher sampling frequency.

The P-DPC algorithm is also more flexible and can be further improved by taking into account other performance criteria like switching frequency and/or power losses minimization.

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