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Simulation and Implementation of a Novel Model-Based DPC for Three-Phase Power Converters

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Abstract – *This paper presents theory, simulation and experimental verification of a new direct power control (DPC) method in comparison with the conventional switching table based method. In the presented strategy, hysteresis comparators and switching table are replaced by a PWM modulator. The required converter voltage in each sampling period is directly calculated based on measured currents and voltages and system parameters through simple equations. Then, a PWM generator synthesizes the switching pulses for the voltage source converter. Strong theoretical background besides simulation and experimental results has proven the excellent performance and verifies the validity of the proposed power control scheme.*

Keywords: *Direct Power Control, PWM Converter*

Nomenclature

P Instantaneous active power
Q Instantaneous reactive power
P_{ref} Commanded instantaneous active power
Q_{ref} Commanded instantaneous reactive power
v_s AC source voltage
v Converter voltage
V_C DC link voltage
E DC link voltage
i Line current
R Resistance between the source and the converter
L Inductance between the source and the converter
C DC link capacitor
ω Angular speed of the AC source voltage
T_{sp} Sampling period
f_{sp} Sampling frequency
f_{sw} Switching frequency
k Sampling instance
S_{error} Power tracking error
ΔL Inductance mismatch

I. Introduction

Due to the rapid expansion of distributed and renewable energy generation such as wind, photovoltaic, and fuel cell etc, that produce DC or AC voltage with variable frequency, there has been a significant increase on the use of voltage source converters (VSC). On the other hand, new power handling systems such as FACTS, D-FACTS, HVDC etc. require sophisticated control of active and reactive power flow between power supply and the electric grid or local loads. 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 and or accurate control of DC-link voltage at the 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. 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

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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 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 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;
- 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 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 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. Besides having the advantages of the conventional switching table based DPC, the proposed strategy 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 need for hysteresis or linear PI controller.

II. Basic Principle of DPC

Figure 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 figure 1 [3]. This method is based on selecting a voltage vector from a look-up table, table I, 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.

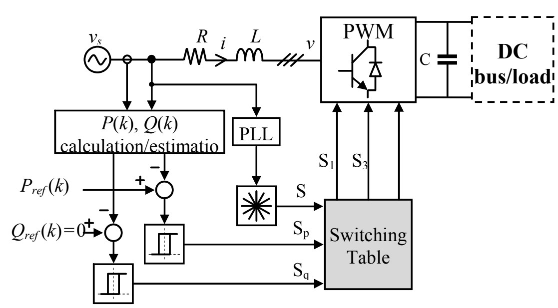


Fig. 1. Basic configuration of DPC for PWM converters [3]

TABLE I
SWITCHING TABLE FOR DPC [3]

S_p S_q	S 1	2	3	4	5	6	7	8	9	10	11	12
0 0	101	100	100	110	110	010	010	011	011	001	001	101
1 0	101	111	100	000	110	111	010	000	011	111	001	000
0 1	100	110	110	010	010	011	011	001	001	101	101	100
1 1	111	111	000	000	111	111	000	000	111	111	000	000

The most significant drawback of 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 [2]-[18]. 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 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 errors 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 computations and may not be viable in industrial applications. Also their performance is highly sensitive to system parameters. Some authors proposed predictive current control algorithms related to power control requirements, but these works present variable switching frequencies [15], [16]. There are some reports, in which authors have tried to improve the performance of the conventional switching table based DPC, by introducing new switching tables, however the results are not considerable [17], [18].

III. Proposed DPC

The authors propose a new method to direct power control of three phase PWM converters that has the following advantages:

- no hysteresis controller and linear PI controller are required and reference values in each sampling period are directly computed based on measurements and system parameters;
- decoupled control of active and reactive powers;
- no need for evaluation of any quality function or any other optimization which are time consuming calculations;
- fast calculation of reference voltage for the modulator by using simple mathematical operations such as plus, minus, multiplication, and division;
- simple algorithm besides strong theoretical background;
- it operates at constant switching frequency thanks to the PWM generator, which makes the use of advanced modulation techniques possible;
- filter design is simple because of the constant switching frequency;
- low switching and sampling frequencies;
- higher dynamic performance due to the fast control strategy.

Figure 2 shows the block diagram of the proposed method. In this configuration, the reference value of the active power usually comes from the DC-link voltage regulator, and the unity power factor operation is achieved by controlling the reactive power to be zero.

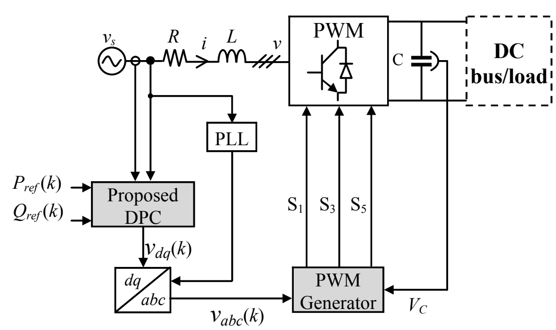


Fig. 2. Proposed DPC for three-phase PWM converters

To derive the equations of the proposed DPC, we start with the following equations obtained from the power circuit of Fig. 2:

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

By applying the Park transformation in the stationary reference frame to (1), then we will obtain:

$$L\frac{d}{dt}\vec{i}_{\alpha\beta} = -R\vec{i}_{\alpha\beta} + \vec{v}_{s\alpha\beta} - \vec{v}_{\alpha\beta} \quad (2)$$

Considering that $\vec{x}_{\alpha\beta} = \vec{x}_{dq}e^{j\omega t}$, (2) will change to (3) in the rotating reference frame:

$$\frac{d}{dt}\vec{i}_{dq} = \left(-\frac{R}{L} - j\omega\right)\vec{i}_{dq} + \frac{1}{L}\vec{v}_{sdq} - \frac{1}{L}\vec{v}_{dq} \quad (3)$$

Equation (3) is discretized using (4) in each small sampling period (T_{sp}) as (5) which then can be decoupled to d and q components as shown in equations set (6):

$$\frac{d}{dt}\vec{i}_{dq} = \frac{\vec{i}_{dq}(k+1) - \vec{i}_{dq}(k)}{T_{sp}} \quad (4)$$

$$\begin{aligned} &\vec{i}_{dq}(k+1) = \\ &= -T_{sp}\left(\frac{R}{L} + j\omega\right)\vec{i}_{dq}(k) + \\ &+ \frac{T_{sp}}{L}\left(\vec{v}_{sdq}(k) - \vec{v}_{dq}(k)\right) + \vec{i}_{dq}(k) \end{aligned} \quad (5)$$

$$\begin{cases} i_d(k+1) = \left(1 - \dfrac{T_{sp}R}{L}\right)i_d(k) + T_{sp}\omega i_q(k) + \\ + \dfrac{T_{sp}}{L}\left(v_{sd}(k) - v_d(k)\right) \\ i_q(k+1) = \left(1 - \dfrac{T_{sp}R}{L}\right)i_q(k) - T_{sp}\omega i_d(k) + \\ + \dfrac{T_{sp}}{L}\left(v_{sq}(k) - v_q(k)\right) \end{cases} \quad (6)$$

On the other hand, the active and reactive powers in the rotating reference frame are:

$$P(k+1) = v_{sd}(k+1)i_d(k+1) + v_{sq}(k+1)i_q(k+1) \quad (7)$$

$$Q(k+1) = v_{sq}(k+1)i_d(k+1) - v_{sd}(k+1)i_q(k+1) \quad (8)$$

During a small sampling period, the AC source voltage can be assumed constant. Besides, by using a PLL the control system will be synchronized with the AC source voltage:

$$v_{sd}(k+1) \cong v_{sd}(k) \quad (9)$$

$$v_{sq}(k+1) \cong v_{sq}(k) = 0 \quad (10)$$

By rearranging (6)-(10) we will have the following equations set for the instantaneous powers (11):

$$\begin{cases} P(k+1) = \left(1 - \dfrac{T_{sp}R}{L}\right)v_{sd}(k)i_d(k) \\ +T_{sp}\omega v_{sd}(k)i_q(k) + \dfrac{T_{sp}}{L}\left(v_{sd}^2(k) - v_{sd}(k)v_d(k)\right) \\ Q(k+1) = -\left(1 - \dfrac{T_{sp}R}{L}\right)v_{sd}(k)i_q(k) \\ +T_{sp}\omega v_{sd}(k)i_d(k) - \dfrac{T_{sp}}{L}v_{sd}(k)v_q(k) \end{cases}$$

The target of the control is to make the load active and reactive powers at the sampling point ($k+1$), equal to the reference active and reactive power values currently available at the sampling point (k), so we will have:

$$P(k+1) = P_{ref}(k) \quad (12)$$

$$Q(k+1) = Q_{ref}(k) \quad (13)$$

By substituting (12) and (13) in (11) and solving them for $v_d(k)$ and $v_q(k)$ the following results will be obtained:

$$\begin{aligned} &v_d(k) = v_{sd}(k) + \left(\frac{L}{T_{sp}} - R\right)i_d(k) + \\ &- \frac{L}{T_{sp}}\frac{P_{ref}(k)}{v_{sd}(k)} + L\omega i_q(k) \end{aligned} \quad (14)$$

$$v_q(k) = \left(\frac{L}{T_{sp}} - R\right)i_q(k) + \frac{L}{T_{sp}}\frac{Q_{ref}(k)}{v_{sd}(k)} - L\omega i_d(k) \quad (15)$$

The above equations are the v_d and v_q components in the rotating reference frame of dq that will satisfy the control conditions of (12) and (13). Usually, in order to achieve a unity power factor, the reactive power is assumed to be zero ($Q_{ref}(k) = 0$).

Equations (14) and (15) show that the dq components of the converter voltage can be directly controlled according to only the reference values of the active and reactive powers, system parameters, and the measured current and voltage of the AC source. The gating signals of the PWM converter will then be produced according to these dq voltage components. In the proposed strategy, the voltage modulator has the dominant dynamics and the controller can almost reach the maximum system dynamic response. Since in the proposed DPC, in spite of the conventional one, which is usually referred to as switching table based DPC (STB-DPC), the hysteresis controllers are eliminated, so the problems of their high gain have been avoided. For example, the control sensitivity to AC current ripples is minimized and consequently the switching and sampling frequencies can be chosen to be small. Furthermore, in the proposed DPC, the gate signals are generated by a PWM modulator instead of the hysteresis regulators, so the switching frequency is constant and much lower than the STB-DPC scheme, and also advanced modulation techniques can be used to achieve higher efficiencies and better harmonics performance.

IV. Simulation Results

In order to verify the effectiveness of the proposed configuration and its control strategy, a digital computer simulation model has been developed in MATLAB/SIMULINK platform. The system parameters are summarized in table II. In order to evaluate the system performance, extensive simulations have been done.

TABLE II
SIMULATION AND EXPERIMENTAL PARAMETERS

Parameter	Value
Input inductance L	10 mH
Input resistance R	200 mΩ
DC-link capacitor C	470 µF
Source phase voltage v_s	70 Vpeak
Source voltage frequency f_s	50 Hz
DC-link voltage E	150 V

IV.1. Steady-State and Transient Performance

The performance of the proposed strategy in steady-state and transient conditions will be verified by simulation results and will be compared with the results of the conventional Switching Table Based-DPC (STB-DPC) and the results of the well-known indirect control method, such as VOC. To assure a valid comparison, both the proposed DPC and VOC utilize SPWM technique with switching frequency (f_{sw}) and sampling frequency (f_{sp}) of 5 kHz. Figures 3 and 4 show the steady-state and step responses of the proposed DPC, STB-DPC and VOC schemes. The steady-state waveforms from STB-DPC and proposed DPC schemes confirm the superiority of the proposed method in providing more precise current control with minimum distortion and less harmonic noises (THD*i*) and at the same time, more accurate regulation and less distortion in the output active and reactive powers, even when the sampling frequency for STB-DPC is ten times that for the proposed method. Indeed, the steady-state performance of the proposed method is comparable with the VOC's. The harmonic spectrum of the phase current ia is shown in figure 5. As it can be seen, the total harmonic distortion (THD*i*) for the proposed method is found to be 1.21%, whereas this value for the STB-DPC is 7.10% and 1.67% with sampling frequencies of 5 kHz and 50 kHz, respectively. One can recognize that the conventional DPC in figures 5-b and 5-c has a broadband harmonic spectrum that spread over a wide low frequency range. Because of these low frequency harmonics the design of filters will be difficult in order to avoid possible grid resonances. As it was expected, the proposed DPC and the VOC produce a similar harmonic spectrum. Figure 4 shows the simulated transient responses. At t=0.025 s the reference value of the active power jumped to 1500 W. Figure 4-a shows that the measured value of the active power converges to the reference value in 0.4 ms; whereas this time for the STB-DPC with f_{sp} = 50 kHz and the VOC is around 1 ms and 2 ms, respectively, as shown in Figures 4-c and 4-d. While both DPC strategies show a better dynamic performance than the VOC scheme, but the proposed DPC has a considerable superiority over the conventional STB-DPC.

IV.2. Effects of Parameters Uncertainty

The operation of model-based controller depends on the system parameters, i.e. L and R. Equations (14) and (15) clearly show that the effect of R when compared to the term L/T_{sp} is negligible. Indeed, the voltage drop on the filter resistance is much lower than the voltage drop on the filter inductance; therefore, it can be ignored. The performance of proposed DPC considering mismatch in the inductance value is investigated and results are depicted in figure 6 in which Serror[%] is defined by.

$$S_{error}[\%] = \sqrt{\frac{\left(P - P_{ref}\right)^2 + \left(Q - Q_{ref}\right)^2}{P_{ref}^2 + Q_{ref}^2}} \times 100 \quad (16)$$

It can be seen that the THD*i* mainly depends on the switching frequency and the load value; however, high positive values of ΔL when the switching frequency is low lead to large current ripples.

On the other hand, at low inductance values, there is a considerable error in power tracking performance whereas overestimated inductance values bring smaller errors.

To eliminate the steady-state error caused by the parameters mismatch and numerical errors, an integral controller with a large time constant can be used. In this way, the integration results of the active and reactive power errors will be added to $v_d(k)$ and $v_q(k)$, respectively. This integrator will ensure the accurate power tracking performance while by using a large time constant, its impact on system dynamic performance can be neglected.

IV.3. Effects of Distorted Line Voltage

Distorted line voltages by 5th harmonic are defined as:

$$\begin{aligned} v_{sa} &= V_{pk}\, sin(\omega t) + k_1 V_{pk}\, sin(5\omega t) \\ v_{sb} &= V_{pk}\, sin\left(\omega t - \frac{2\pi}{3}\right) + k_1 V_{pk}\, sin\left(5\omega t + \frac{2\pi}{3}\right) \\ v_{sc} &= V_{pk}\, sin\left(\omega t + \frac{2\pi}{3}\right) + k_1 V_{pk}\, sin\left(5\omega t - \frac{2\pi}{3}\right) \end{aligned} \quad (17)$$

The controller performance is evaluated for different values of k_1. For $k_1 = 0$, as shown in Figs. 5, THDi = 1.21%, while for $k_1 = 0.02$ and 0.05 this value becomes 2.35% and 4.96%, respectively; so, the proposed DPC still provides sinusoidal line currents with low distortions.

IV.4. Effects of Imbalanced Line Voltage

Considering positive and negative sequence components, the line voltages are defined as

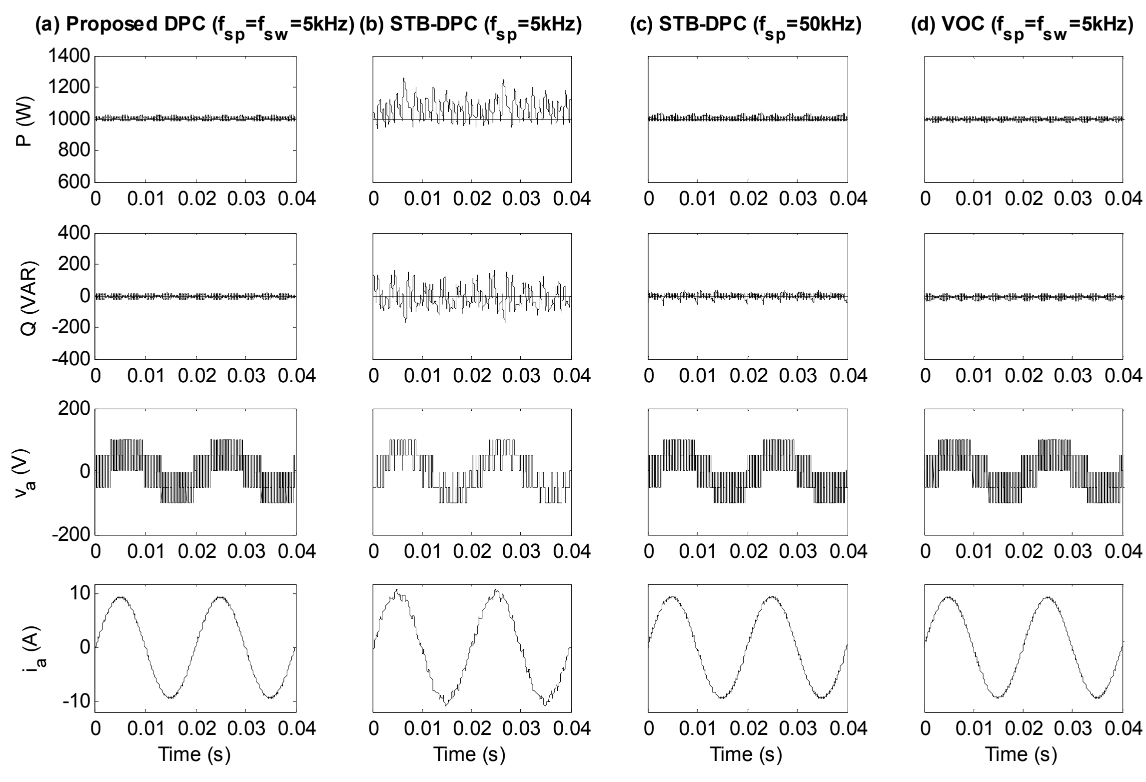
$$\begin{aligned} v_{sa} &= V_{pk}\, sin(\omega t) + k_2 V_{pk}\, sin(\omega t) \\ v_{sb} &= V_{pk}\, sin\left(\omega t - \frac{2\pi}{3}\right) + k_2 V_{pk}\, sin\left(\omega t + \frac{2\pi}{3}\right) \\ v_{sc} &= V_{pk}\, sin\left(\omega t + \frac{2\pi}{3}\right) + k_2 V_{pk}\, sin\left(\omega t - \frac{2\pi}{3}\right) \end{aligned} \quad (18)$$

Under imbalanced conditions, the quality of PLL mainly determines the distortion in line current.

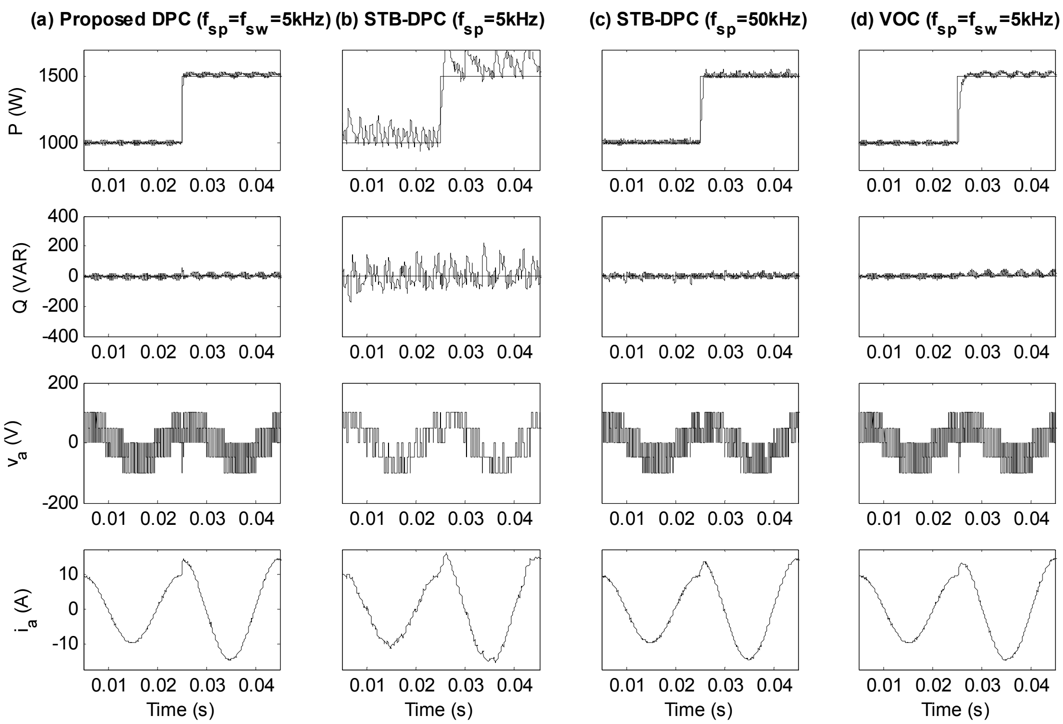
We have used a simple arctan function to calculate the line voltage angle position from its $\alpha\beta$ components. In this case, for k_2= 0.02 and 0.05 the values of THDi = 2.41% and 5.2% are obtained, respectively. T

his simple PLL can keep the THDi near its acceptable value; however, principally, by using a more complicated phase detection method, much lower THDi values can be obtained under imbalanced operation. This can be the scope of another work.

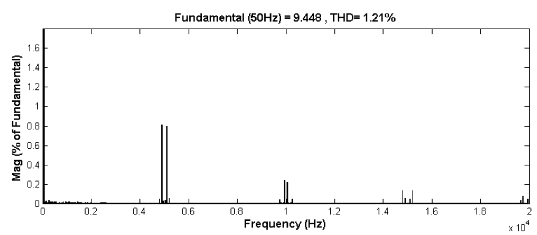
Table III compares the THDi values for different control strategies under distorted and imbalanced line voltages. One can see that under such conditions, the THDi values for VOC are slightly lower than those for the proposed method.



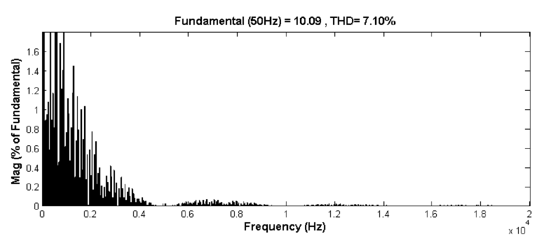
Figs. 3. Simulated waveforms for steady-state operation



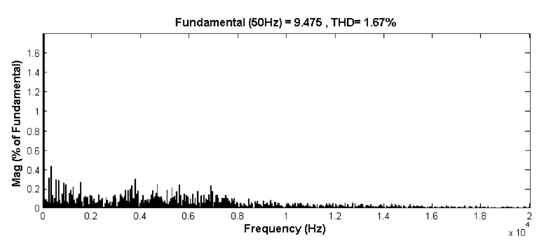
Figs. 4. Simulated waveforms for step change of active power



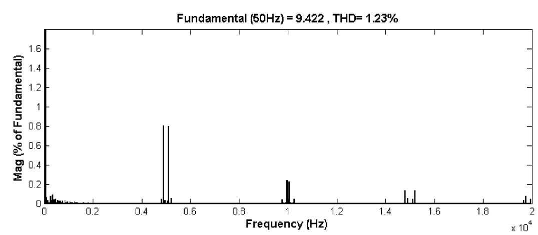
(a) Proposed DPC (f_{sp}=f_{sw}=5kHz)



(b) STB-DPC (f_{sp}=5kHz)



(c) STB-DPC (f_{sp}=50kHz)



(d) VOC (f_{sp}=f_{sw}=5kHz)

Figs. 5. Simulated line current harmonic spectrum
(P_{ref}= 1000 W, Q_{ref}= 0)

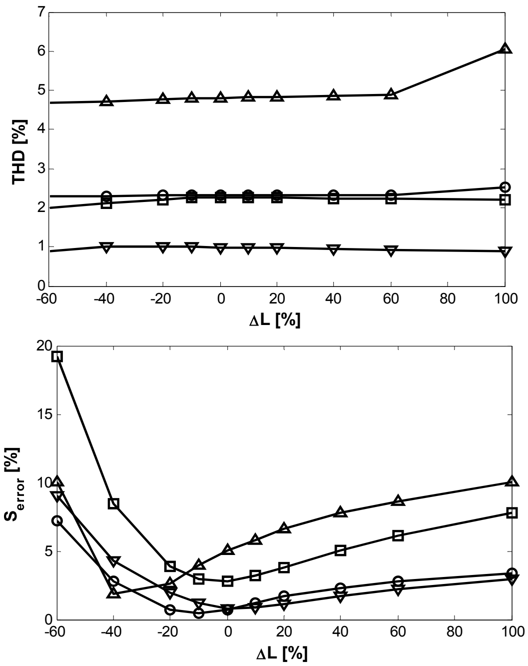
TABLE III
THD [%] AS A FUNCTION OF 5TH HARMONIC AND VOLTAGE IMBALANCE (P_{ref} = 1000 W, Q_{ref} = 0)

k_1, k_2	Proposed DPC f_{sp}=f_{sw}=5kHz	STB-DPC f_{sp}=5kHz	STB-DPC f_{sp}=50kHz	VOC f_{sp}=f_{sw}=5kHz
0, 0	1.21	7.10	1.67	1.23
0.02, 0	2.35	7.51	2.31	2.09
0.05, 0	5.07	8	5.04	4.06
0, 0.02	2.34	8.57	2.51	2.27
0, 0.05	5.2	9.73	5.26	5.02

V. Experimental Results

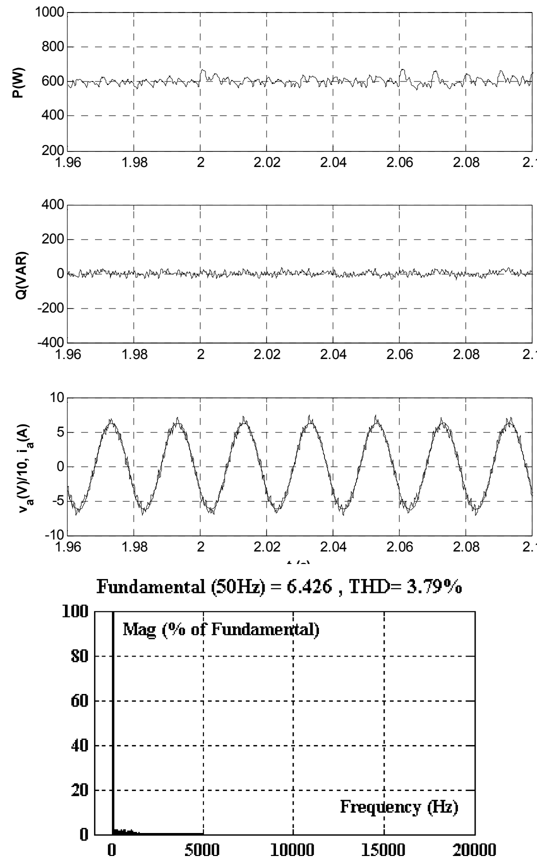
Fig. 7 shows the experimental test bench implemented to verify the effectiveness of the proposed scheme. The control strategy is developed using MATLAB/SIMULINK Real Time Windows Target. The sampling frequency for the experimental implementation was chosen to be 10 kHz, and experimental results are obtained with the same parameters used in the simulations. The DC side of the converter is connected to a fixed 42 Ω resistive load. Experimental results are presented in Figs. 8 and 9.

Steady-state waveforms, which confirm the proper operation of the proposed DPC, are presented in figure 8. The quality of practical converters is normally evaluated in terms of the total harmonic distortion (THD*i*). Based on the IEEE standard, this value should be less than 5%; so one can recognize that the proposed strategy provided acceptable THD*i* as shown in Figs. 8.

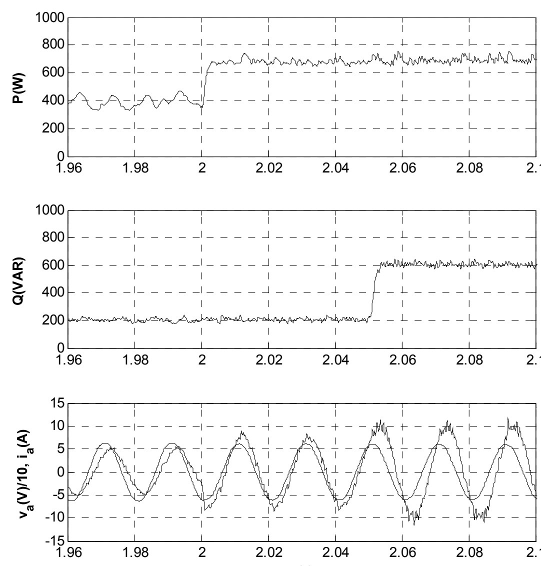


Figs. 6. Effect of inductance mismatch ΔL[%] on current THD and steady-state power errors;
□ $f_{sp} = f_{sw} = 2$ kHz, $P_{ref} = 1500$ W, $Q_{ref} = 0$
△ $f_{sp} = f_{sw} = 2$ kHz, $P_{ref} = 500$ W, $Q_{ref} = 0$
○ $f_{sp} = f_{sw} = 5$ kHz, $P_{ref} = 500$ W, $Q_{ref} = 0$
▽ $f_{sp} = f_{sw} = 5$ kHz, $P_{ref} = 1500$ W, $Q_{ref} = 0$

Fig. 7. Experimental setup



Figs. 8. Experimental results for steady-state operation; active power, reactive power, line voltage and current and line current harmonic spectrum ($P_{ref} = 1000$ W, $Q_{ref} = 0$)



Figs. 9. Experimental results for step change of active and reactive power; active power, reactive power and line voltage and current

The dynamics of the PWM converter with the proposed scheme is presented in figure 9.

The experimental results confirm that the proposed control strategy decoupled the active and reactive powers very well. Also, shown in figure 9, the response following a step change in the active or reactive power command is very fast, which proves the excellent dynamics.

VI. Conclusion

A novel method for direct power control (DPC) of three-phase pulse-width-modulated (PWM) converters is presented.

In this method, hysteresis comparators and switching table of a conventional DPC scheme are replaced by the PWM modulator.

Simulation and experimental results confirm the superiority of the proposed method in providing more precise power control with minimum distortion and harmonic noises (THD*i*), and at the same time, less distortion in active and reactive powers, narrower current harmonic spectrum and faster dynamics compared to conventional DPC scheme.

From simulation and experimental results, the proposed strategy besides having the conventional method’s advantages offers many unique features such as:

- more precise control and better regulation performance than the STB-DPC;
- higher dynamic behavior (less convergence time);
- narrower harmonic spectrum than STB-DPC;
- less total harmonic distortion (THD*i*) than STB-DPC;
- fixed switching frequency, also it requires less sampling and switching frequencies because of simpler and more precise algorithm which eliminates the hysteresis controllers.

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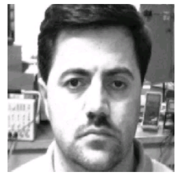

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