

## Implementation of Voltage Oriented Control of 3-Phase PWM Rectifier, via. Fuzzy and PI Controller for Output Voltage Regulation

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**Abstract:** This study proposes the implementation of Voltage Oriented Control (VOC) for three phase PWM rectifier. The basic principles of the PWM rectifier are analyzed and then the 3-phase mathematical of the input AC voltage sensorless PWM rectifier control system is established in synchronous rotating coordinates dq. The main goal of the control system is to maintain the dc output voltage at the desired value while input currents should be sinusoidal with minimum current harmonic and in phase with respective phase voltages in order to satisfy the unity power factor operation. Moreover, a comprehensive comparison of the DC-bus voltage control will be undertaken between IP controller and fuzzy controller to obtain the active power control. A Dspace based experimental system was developed to verify the validity of the proposed VOC. Compared with IP controller fuzzy controller gives excellent performance in transient state, good rejection of impact load disturbance and a good robustness.

**Key words:** PWM rectifier, VOC, fuzzy logic controller, PI controller, decoupled controller, THD

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### INTRODUCTION

Converters in the AC to DC conversion field are the most widespread and the operation of a converter can be explained in terms of the input quantities, output quantities and the switching pattern used to obtain the preferred output.

The capacity to control the system to obtain unity power factor operation of a boost rectifier is an important feature of the rectifier topology. The power quality problems such as large values of harmonics, poor power factor and high total harmonics distortion are usually associated with operations of AC to DC converters. An increase in the current harmonics and a decrease in the displacement power factor in AC power lines produced by diode and thyristor are serious problems (Bhattacharya, 2014; Lamterkati *et al.*, 2016).

Many control strategies were proposed in recent work for the PWM rectifier to reduce current harmonics and improve the power factor in the power grid and according to inner loop control objects, PWM rectifier control methods can be subdivided into two groups. They are Direct Power Control (DPC) and Voltage Oriented Control (VOC) (Malinowski *et al.*, 2003; Kazmierkowski and Malesani, 1998; Giglia and Pucci, 2008). DPC is based on instantaneous direct active and reactive power control loops. In this method, there are no internal current control loops and no PWM modulator block because the

converter switching states are appropriately selected by a switching table based on the instantaneous errors between the reference and calculated values of active and reactive power. VOC is the most traditional control scheme and has been fully researched and is the method that we used in this study. The Voltage Oriented Control (VOC) or Virtual Flux Orientation Control (VFOC) can be implemented because both methods have some advantages (Gadoue *et al.*, 2009; Lamterkati *et al.*, 2016):

- Fixed switching frequency which makes easier to design the input filter
- Low sampling frequency for good performance
- Advanced PWM is feasible with this control
- AC/DC converters are cheap

These control methods have also some disadvantages it is necessary to deal with:

- Decoupling between active and reactive power is required
- Complex algorithm
- Input power factor is lower than DPC or VF-DPC

The method is based on the transformation between stationary coordinate's  $\alpha\beta$  and synchronous rotating coordinates dq. This can guarantee high dynamics and

static performances by internal loops of current control (Semmah *et al.*, 2011; Malinowski *et al.*, 2001) and achieves unity power factor operation by controlling the AC side current vector which rotates with AC side voltage vector synchronously (Wu, 2012). Switching signals of each bridge arm can be produced by sinusoidal PWM or Space Vector PWM (SVPWM). Final configuration and performances of the VOC technique depend largely on the quality of the current control strategy (Kazmierkowski and Malesani, 1998; Semmah *et al.*, 2011).

This research, we propose a comparison between two methods of DC voltage controller. In the first type, one will use an PI regulator whole integral and proportional actions offer to the system a minimal overshoot and a good response time. In the second type of control, fuzzy controller based human knowledge is introduced to improve the excellent performance in transient and steady state, a good robustness, a good dynamic behavior for dc-bus voltage regulation and a good rejections to the disturbance of load.

**MATERIALS AND METHODS**

**Modeling of three-phase PWM rectifier:** A power circuit of the 3-phase VSR is shown in Fig. 1a. The rectifier is connected to the three phase AC source via. smoothing inductors L and internal resistance R. the inductance act as a line filter for smoothing the lines currents with minimum ripples. Six power transistors (IGBTs) with anti-parallel diodes are used as the VSR power switches, since, IGBTs have features of high power rating which is used to carry out the PWM generation as well as the power bidirectional conversion, a load and capacity are connected simultaneously at the output of the converter. The capacity is used as a voltage source and allows the rectifier to also operate as an inverter (Lamterkati *et al.*, 2014).

The model of the converter can be simplified as it is presented on Fig. 1b. The state of switches in each of the leg can be described using switching function defined in Eq. 1:

$$S_k(t) = \{0, 1\}, \quad k = a, b, c \quad (1)$$

There are 6 actives states of converter for  $S_a+S_b+S_c = \{1, 2\}$  and two passive states for  $S_a+S_b+S_c = \{0, 3\}$ . In each of the active state there exists a circuit for energy transfer between the DC and AC side.

Using the switching function model and by assuming a balance three-phase and three wires system, the voltage equations of the PWM rectifier can be described by Eq. 2-6:

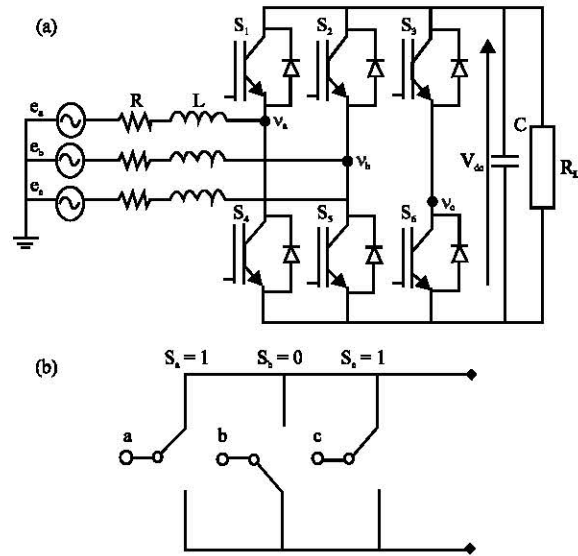


Fig. 1: a) Circuit model and b) Simplified switching model of the 3-phase VSR

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

$$C \frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_{dc} \quad (3)$$

where,  $S_{a,b,c}$  is switching state of the converter. The phase voltages at the poles of the converter are equal to:

$$v_a = (2S_a - (S_b + S_c))/3 \times V_{dc} \quad (4)$$

$$v_b = (2S_b - (S_a + S_c))/3 \times V_{dc} \quad (5)$$

$$v_c = (2S_c - (S_b + S_a))/3 \times V_{dc} \quad (6)$$

**VOC of a 3-phase PWM boost rectifier:** The voltage oriented control is based on a succession of transformations from a 3-phase stationary reference system abc to a synchronous rotating reference system dq through a two phase stationary reference system  $\alpha\beta$  with these transformations, the control voltages remain constant and become DC values, making all the control process more simple.

**Control method description:** In voltage oriented control the VSR is modeled as a AC voltage controlled source  $V_{dc}$ . the principle of operation is explained by connecting the rectifier to the grid via. a line impedance (R, L). The 3-phase source transfers power to/from the DC bus. In Fig. 2, the converter is fully defined by:

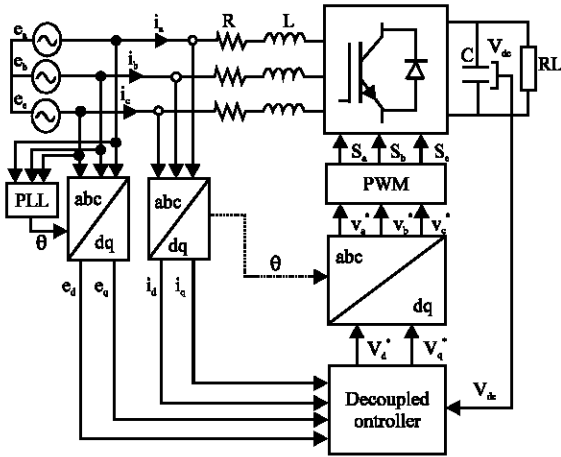


Fig. 2: Voltage oriented control scheme

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (7)$$

By applying the park transformation in the stationary reference frame to Eq. 7, then we will obtain:

$$\vec{e}_{\alpha\beta} - \vec{v}_{\alpha\beta} = L \frac{d}{dt} \vec{i}_{\alpha\beta} + R \vec{i}_{\alpha\beta} \quad (8)$$

Considering that  $\vec{x}_{\alpha\beta} = \vec{x}_{\alpha\beta} e^{j\omega t}$ , Eq. 8 will change to Eq. 9 in SRF:

$$\vec{e}_{dq} - \vec{v}_{dq} = L \frac{d}{dt} \vec{i}_{dq} + (R + jL\omega) \vec{i}_{dq} \quad (9)$$

Equation 9 is decoupled to d and q components and transformed to the Laplace domain as shown in equation set Eq. 10 where S in the Laplace operator:

$$\begin{cases} e_d - v_d = (Ls + R)i_d + L\omega i_q \\ e_q - v_q = (Ls + R)i_q - L\omega i_d \end{cases} \quad (10)$$

It is clear from Eq. 10 that the converter equations in the d and q axes are coupled to each other through  $L\omega i_q$  and  $L\omega i_d$  terms.

Different control strategies have been proposed for this 3-phase boost operation (Malinowski, 2001). If  $i_q = 0$  and  $e_q = 0$  the active and reactive power equations will be simplified to  $p = 3/2 e_d i_d$  and  $q = 0$ . Based on these equations, the feedforward current control method is one of the widely used schemes for power control. Figure 3 shows the basic diagram of the controller. The dq current control and feedforward compensation are the main parts

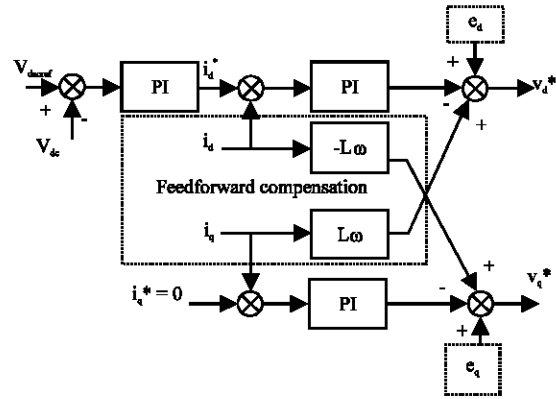


Fig. 3: Decoupled current control

of this decoupled control scheme. The controller has an outer loop for the DC bus voltage regulation. This controller output sets the reference value for the d component of the current that controls the power (Mandiola *et al.*, 2012).

**Design controlling system of the current inner loop:** The PWM modulator delay and the sampling and calculation time of the discrete control system are included in this model as a pure time delay  $T_d$ . A time delay of  $T_d$  in the Laplace domain is described as  $e^{-T_d s}$ . In order to include the effect of control delay in the system modeling and controller design  $e^{-T_d s}$  is replaced by a first order lag approximation  $1/(T_d s)$  (Zarif and Monfared, 2015).

Also, from the control point of view, adding the feedforward term  $e_d$  to the controller output reduces the feedback control effort and offers faster and at the same time smoother transient response, especially at start-ups. The simplified structure of current inner loop is shown in Fig.4.

The resultant control scheme in presence of the decoupling and feedforward expressions is depicted in Fig. 4a which can be readily redrawn as Fig. 4 b.

**DC voltage PI controller:** By importing control variable  $V_{dref}$  the voltage-outer loop is added to control system through which DC-side voltage can remain steady.

For the main function of the voltage-outer-loop is making the DC-side voltage remain steady, the primary target of the system should be enhancing the anti interference performance. So, the system can be designed according to typical system 2. The simplified structure of the voltage-outer-loop is shown in Fig. 5 (Blasko and Kaura, 1997). The transfer function of voltage regulation is:

$$G_v(s) = k_{vp} \frac{1+T_v}{T_v s} \quad (11)$$

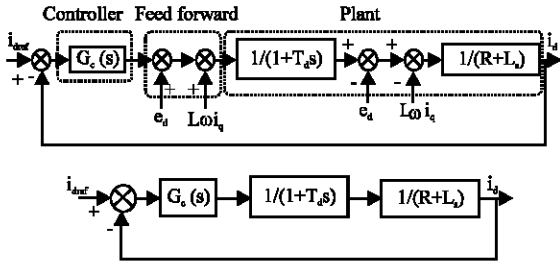


Fig. 4: a) Controlling structure of current inner loop and b) Simplified representation (d-axis)

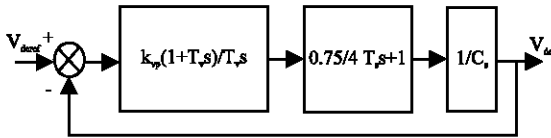


Fig. 5: Equivalent control closed loop of DC voltage

Where:

$$k_{vi} = \frac{k_{vp}}{T_v} \quad (12)$$

By Fig. 5, the open transfer function of system can be expressed as:

$$F_{ov}(s) = \frac{0.75k_{vp}(1+sT_v)}{CT_v s^2(4T_v s + 1)} \quad (13)$$

$$\frac{0.75k_{vp}}{CT_v} = \frac{h_v + 1}{32h_v^2 T_v^2} \quad (14)$$

where,  $h_v = T_v/4T_s$  is the frequency width in the voltage loop, take  $h_v = 5$ , then  $T_v = 20 T_s$ . Finally, the result obtained is:

$$\begin{cases} k_{vp} = \frac{C}{5T_s} \\ k_{vi} = \frac{k_{vp}}{20T_s} \end{cases} \quad (15)$$

**Fuzzy controller:** To have a good performance of DC-bus voltage control, especially in the case of reference DC voltage step variation and load disturbance. The PI controller will be replaced by a fuzzy regulator. The block diagram of this of this control is given by Fig. 6 (Gadoue *et al.*, 2009; Bouafia *et al.*, 2009; Ouboubker *et al.*, 2014).

The fuzzy regulator uses two inputs: the first input is the error between the reference and the measured value of the DC voltage. The second one represents the variation of this error. These two signals are expressed by:

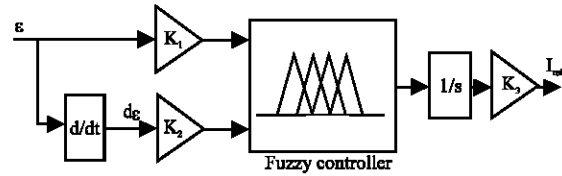


Fig. 6: DC voltage fuzzy control

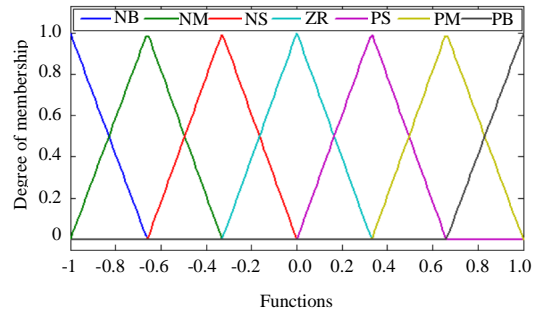


Fig. 7: Membership functions of input and output

Table 1: Fuzzy rules

$\Delta e$	$\epsilon$						
	PB	PM	PS	ZR	NS	NM	NB
NB	<b>ZR</b>	NS	NM	NB	NB	NB	NB
NM	PS	<b>ZR</b>	NS	NM	NB	NB	NB
NS	PM	PS	<b>ZR</b>	NS	NM	NB	NB
ZR	PB	PM	PS	<b>ZR</b>	NS	NM	NB
PS	PB	PB	PM	PS	<b>ZR</b>	NS	NM
PM	PB	PB	PB	PM	PS	<b>ZR</b>	NM
PB	PB	PB	PB	PB	PM	PS	<b>ZR</b>

Bold values are operating points

$$\begin{aligned} \epsilon &= V_{dref}(n) - V_{dc}(n) \\ \Delta \epsilon(n) &= \epsilon(n) - \epsilon(n-1) \end{aligned} \quad (16)$$

For fuzzification, we used triangular membership functions for the error, the variation error and output. We chose the seven fuzzy sets: NB Negative Big, NM Negative Medium, NS Negative Small, ZR Zero, PS Positive Small, PM Positive Medium and PB Positive Big (Malinowski *et al.*, 2001).

The membership functions of the fuzzy controller inputs and output are all the same Fig. 7. Table 1 shows the fuzzy rules base with 49 rules which can be obtained from observation of the control performance at different operating points (Lai and Lin, 2003; Gadoue *et al.*, 2009).

## RESULTS AND DISCUSSION

To validate the effectiveness of the control strategy studied in this study, a digital simulation was carried out under MATLAB/Simulink environment and the real time implementation with Dspace (DS1104) card board inserted into computer. The main electrical parameters of the power circuit and control data used in simulation are given in Table 2.

Table 2: Electrical parameters

Parameter	Values
Line to line ac voltage U	70 V
Source voltage frequency f	50 Hz
Resistance of reactor R	0.2 Ω
Inductance of reactor L	10 mH
Dc-bus capacity C	1.1 mF
Load resistance RL	64 Ω
Dc-bus voltage $V_{dc}$	125 V
Switching frequency $f_c$	10 KHz

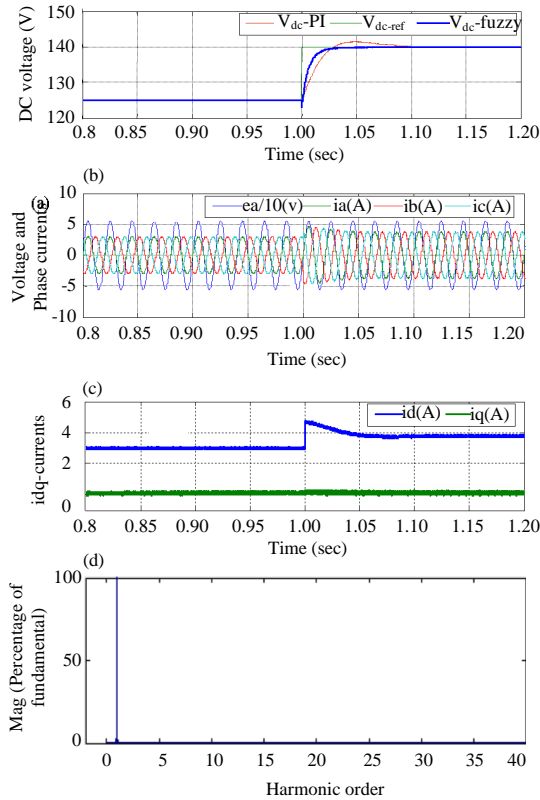


Fig. 8: Transient of the step change of  $V_{dcref}$  for the VOC with PI controller, increasing from 125-140 V; a) DC-link voltage; b) Voltage and line currents; c) dq currents and d) Current harmonic spectrum

**Simulation results:** Various tests in both simulations and real implementation were conducted to verify feasibility and performance of the proposed VOC. Figure 8-10 show the dynamic behavior of the fuzzy controller under a step change of  $V_{dcref}$  for the classical VOC and new VOC, respectively.

From this figures, it can be seen the results obtained with the fuzzy controller are much better than those of PI controller. DC-bus voltage presents a better transient response and does not present any overshoot. Line currents are very close to sine wave (THD = 1.92%) and in phase with power source voltages.

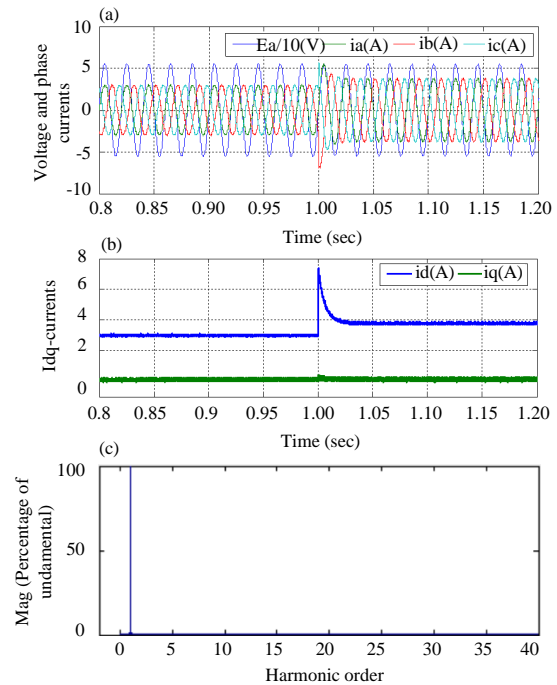


Fig. 9: Transient of the step change of  $V_{dcref}$  for the VOC with fuzzy controller, increasing from 125-140 V: a) Voltage and line currents; b) dq currents and c) Current harmonic spectrum

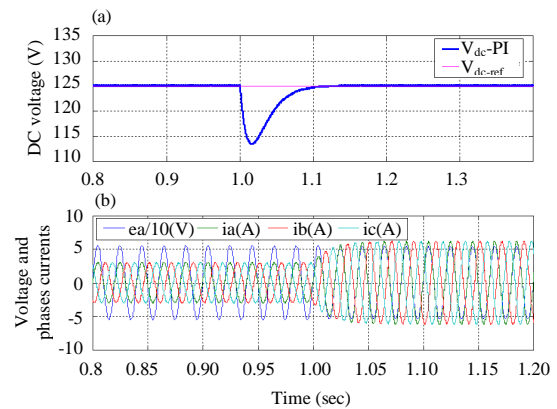


Fig. 10: Transient of the step change of the load (load Increasing 50%) with PI controller: a) DC-link voltage and b) Voltage and grid currents

Figure 11 and 12 show the results of a step response against the disturbance load power under the unity power factor operation. It does can be observed that the unity power operation is successfully achieved, even in this transient state. Notice that, after a short transient, the output voltage is maintained close to its reference value.

**Experimental results:** Based on the above analysis an experimental prototype has been constructing to examine

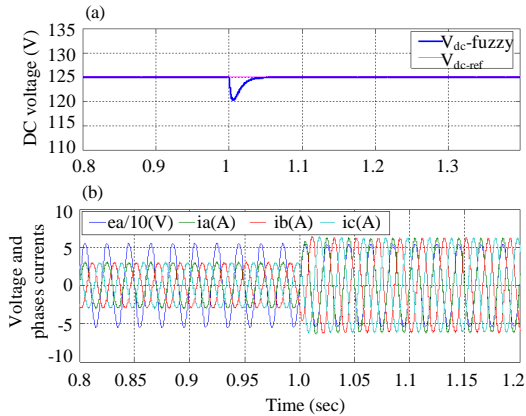


Fig. 11: Transient of the step change of the load (load increasing 50%) with fuzzy controller: a) DC-link voltage and b) Voltage and grid currents

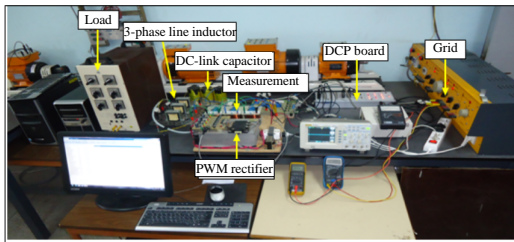


Fig. 12: Different parts of experimental test bench and its dspace control

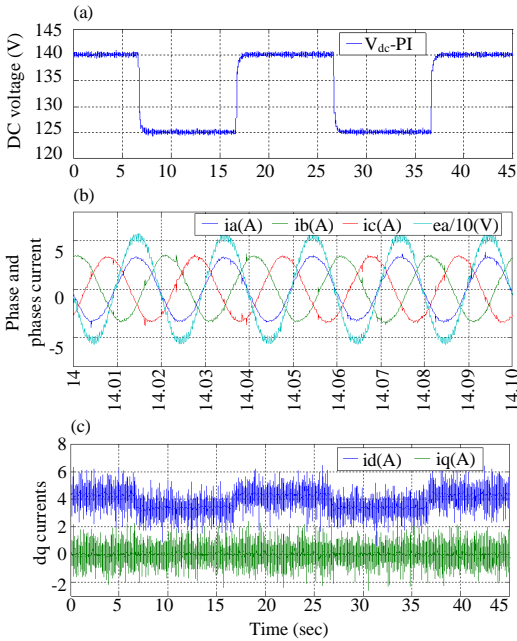


Fig. 13: Transient of the step change of  $V_{dcref}$  (Increasing from 125-140 V with PI controller: a) DC-link voltage; b) Voltage and grid currents and c) dq-currents

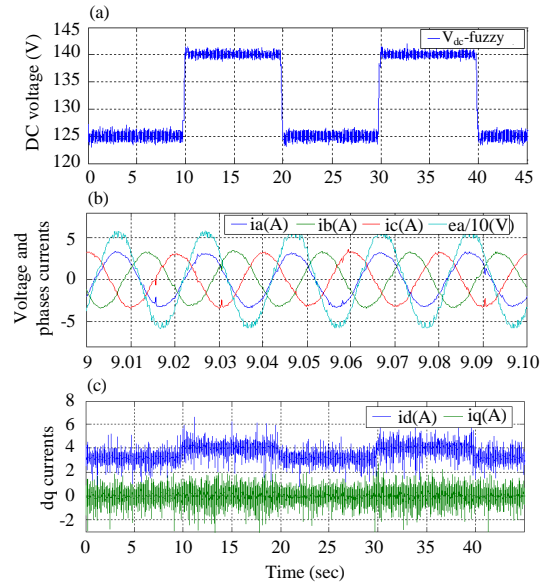


Fig. 14: Transient of the step change of  $V_{dcref}$  (Increasing from 125-140 V with fuzzy controller: a) DC-link voltage; b) Voltage and grid currents and c) dq-currents

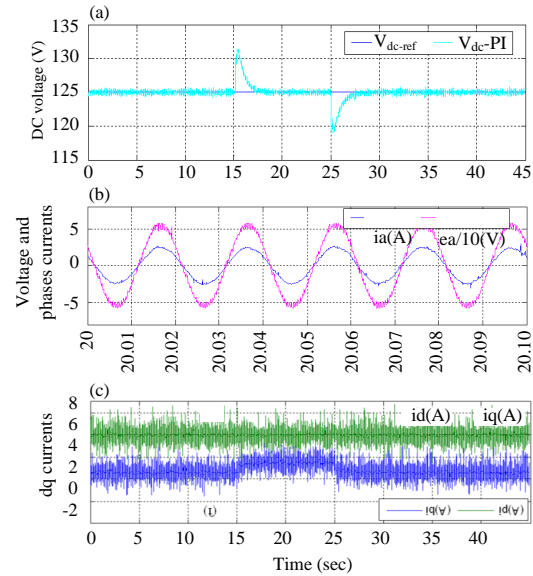


Fig. 15: Transient of the step change of load power with PI controller: a) DC-link voltage; b) Voltage and grid current and c) dq-currents

the theoretic and the simulation. A Dspace system with DS1104 controller board and a 3 phase IGBT inverter as it is shown in Fig. 13. The corresponding experimental results, for the classic VOC and fuzzy VOC are presented in Fig. 14 and 15, respectively.

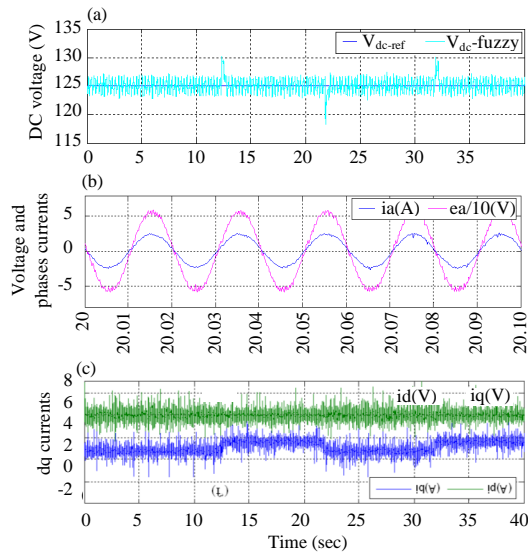


Fig. 16: Transient of the step change of load power with fuzzy controller: a) DC-link voltage; b) Voltage and grid currents and c) dq-currents

The dynamic behavior of the fuzzy VOC under a step change of  $V_{dc-ref}$  is presented in Fig. 15. After a short transient, the DC-bus voltage is maintained close to its new reference with good approximation and stability. The line currents have nearly sinusoidal waveform. From this figure, it can be found that the active current control and the reactive current control are independent of each other and achieve unit power factor ( $\dot{i}_q = 0$ ).

Figure 16 shows experimental results of a step response to the variation load under the unity power factor operation. It can be observed that the unity power factor operation is successfully achieved, even in this transient state. Notice that, after a short transient, the DC-voltage and active current are maintained close to their reference values. The reactive current is maintained zero. It is clear, from these figures that the transient response in the DC-bus voltage and the active current is faster with the fuzzy controller.

### CONCLUSION

This study has presented the development of the new Voltage Oriented Control (VOC) scheme for 3-phase PWM rectifier using a fuzzy control system on the DC side. The main goal of the proposed control strategy is to achieve near-sinusoidal input current waveforms of the converter under different input voltage conditions and maintaining the dc-bus voltage at the required level. Meanwhile, the rectifier's practical realization is simpler than using conventional PI controller. Moreover, the design was

proved to be correct and reasonable by experiments that based on Simulink toolbox. Simulation and experimental results have proven a superiority of the conventional VOC for the static performance and a superiority of fuzzy VOC for the dynamic performance. In fact, fuzzy VOC gives excellent dynamic performance, a good rejection of impact load disturbance and a good robustness.

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