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# A Fuzzy-Logic-Based Controller for Three-Phase PWM Rectifier With Unity Power Factor Operation

***In this paper, direct power control (DPC) of three-phase PWM rectifiers based on fuzzy logic controller is presented, without line voltage sensors. The control technique is built upon the ideas of the well known direct torque control (DTC) for induction motors. 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 proposed fuzzy logic controller presents the advantage to be based on linguistic description and does not require a mathematical model of the system. The controller ensures a good regulation of the output voltage, and guarantees the power factor close to one. The simulation results show that the designed fuzzy controller has a good dynamic behavior, a good rejection of impact load disturbance, and is very robust.***

**Keywords:** Direct power control, Fuzzy logic control, PWM Rectifier, instantaneous active and reactive power, Switching table.

## 1. NOMENCLATURE

| | |
|---|---|
| $v_{a,b,c}$, $i_{a,b,c}$ | Input line voltages and currents. |
| $S_a$, $S_b$, $S_c$ | Swhiching states of the converter. |
| $v_{dc}$ | dc-bus voltage. |
| $L$ | Inductance of interconnecting reactors. |
| $R$ | Resistance of interconnecting reactors. |
| $C$ | dc-link capacitor. |
| $R_L$ | Load resistance. |
| $\alpha,\beta$ | Alpha, beta components. |
| $\theta_n$ | The phase of power source voltage vector. |
| $P$ | Instantaneous active power. |
| $q$ | Instantaneous reactive power. |
| $S_P$, $S_q$ | Hysterisis comparators output. |
| ^ | Estimated value. |
| * | Reference value. |
| e(k) | Error at the k$^{th}$ sample instant. |
| $\Delta$e(k) | Incremental variation of error. |

## 2. INTRODUCTION

Research interest in three-phase pulse width modulated (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-bus voltage, low harmonic distortion of input currents, and high power factor (usually, near unity). Various control strategies have being proposed in recent works on this type of PWM rectifier. A well-known method of indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector [voltage-oriented control (VOC)] [1]-[6].

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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 less known method based on instantaneous direct active and reactive power control is called direct power control (DPC) [7]-[10]. The idea behind this technique consists in selecting a control vector from a look up table based on the error of instantaneous active and reactive powers as well as on the angular position of the voltage source vector. The input space (in the plane) is divided in twelve sectors.

In most DPC schemes for PWM rectifier, an external PI loop utilising the dc-voltage error is used to compute the desired active power. This PI controller requires precise linear mathematical models, which are difficult to obtain and fails to perform satisfactory under parameter variations, nonlinearity, load disturbance, etc.

This paper presents a direct power control (DPC) of three-phase PWM rectifier based on fuzzy logic control approach; 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 dc-bus voltage is regulated by controlling active power using fuzzy logic controller, which provides active power command *P**. While the reactive power command *q** is set to zero to achieve unity power factor operation. Finally, the developed fuzzy controller is compared with conventional PI controller. It is shown via simulation results that the proposed controller based on fuzzy logic control gives good performance, a good rejection of impact load disturbance, a good dynamic behaviour for dc output voltage regulation and is very robust.

## 3. PRINCIPLES OF DPC BASED FUZZY CONTROL

The schematic diagram of a three phase PWM rectifier with DPC algorithm is shown in Fig.1. The ac source voltages are $v_a$, $v_b$ and $v_c$. The ac currents are $i_a$, $i_b$ and $i_c$. The ac terminal voltages of the PWM rectifier are $u_a$, $u_b$ and $u_c$ . The dc voltage and current are $v_{dc}$ and $i_{dc}$ respectively. The ac side impedance is modelled as an inductor L in series with a resistor R. The dc side capacitor is C and the dc load is $R_L$. The modulation signals of phases a, b and c are $S_a$, $S_b$ and $S_c$.

The voltage equation in the stationary a-b-c frame is: [11]-[12]

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{1}$$

In the stationary reference frame α-β the voltage equation can be represented as:

$$\begin{bmatrix} v_\alpha \\ v\beta \end{bmatrix} = R\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{2}$$

By transforming (2) into synchronous rotating reference frame d-q, the voltage equation in the synchronous d-q coordinates is derived as:

$$\begin{aligned} v_d &= R.i_d + L\frac{di_d}{dt} - \omega.L.i_q + u_d \\ v_q &= R.i_q + L\frac{di_q}{dt} + \omega.L.i_d + u_q \end{aligned} \tag{3}$$

The ac terminal voltages of the PWM rectifier $u_a$, $u_b$ and $u_c$, are computed from the output dc voltage and switching signals $S_a$, $S_b$ and $S_c$ as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{v_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{4}$$

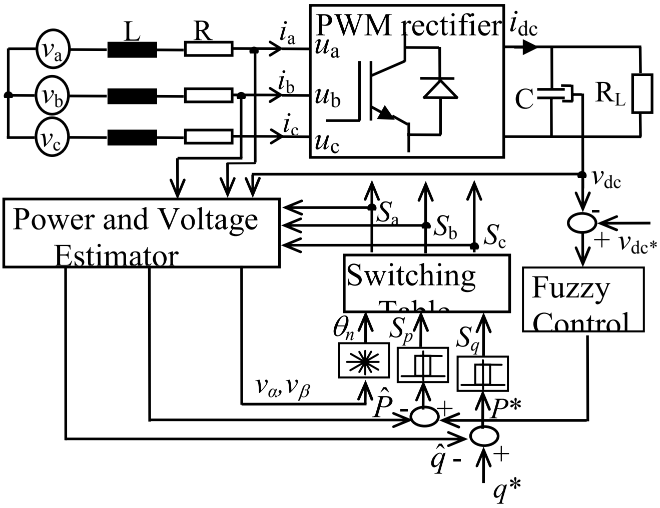


Fig.1. Configuration of DPC based on fuzzy controller for three-phase PWM rectifier.

DPC of three-phase PWM rectifier is based on the instantaneous active and reactive power control loops [7]-[10]. In DPC there are no internal current control loops and no PWM modulator block, because 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 based on fuzzy controller for three-phase PWM rectifier.

Hereafter, it is assumed that the value of *R* is negligibly small and the switching devices in the converter are functionally ideal, i.e., they require no lockout function and have no forward voltage drops.

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 controlling the active power using fuzzy logic controller, 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 fuzzy 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 $S_p$, $S_q$. where:

$S_p$=1 if $p^* - \hat{p} \geq h_p$, $S_p$=1 if $p^* - \hat{p} \leq - h_p$

$S_q$=1 if $q^* - \hat{q} \geq h_q$, $S_q$=1 if $q^* - \hat{q} \leq - h_q$

Also, the phase of the power-source voltage vector is converted to the digitized signal $\theta_n$. For this purpose, the stationary coordinates are divided into 12 sectors, as shown in Fig.2, and the sectors can be numerically expressed as:

$$(n-2)\frac{\pi}{6} \leq \theta_n \leq (n-1)\frac{\pi}{6} \quad n=1,2,\ldots\ldots,12 \tag{5}$$

The digitized error signals $S_p$ and $S_q$ and digitized voltage phase $\theta_n$ are input to the switching table in which every switching state, $S_a$, $S_b$, and $S_c$, of the converter is stored, as shown in Table I.

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.

The selection of the optimum switching state is performed so that the power errors can be restricted within the hysteresis bands.

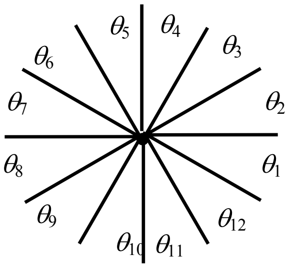


Fig.2. Twelve sectors on stationary coordinates to specify voltage phase.

TABLE I

Switching Table for Direct Instantaneous Power Control.

| $S_p$ | $S_q$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ | $\theta_7$ | $\theta_8$ | $\theta_9$ | $\theta_{10}$ | $\theta_{11}$ | $\theta_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 101 | 111 | 100 | 000 | 110 | 111 | 010 | 000 | 011 | 111 | 001 | 000 |
|  | 1 | 111 | 111 | 000 | 000 | 111 | 111 | 000 | 000 | 111 | 111 | 000 | 000 |
| 0 | 0 | 101 | 100 | 100 | 110 | 110 | 010 | 010 | 011 | 011 | 001 | 001 | 101 |
|  | 1 | 100 | 110 | 110 | 010 | 010 | 011 | 011 | 001 | 001 | 101 | 101 | 100 |

It is known that the calculation of the active power $P$ is a scalar product between the voltages and the currents, whereas the reactive power $q$ can be calculated by a vector product between them [13]-[15].

$$p = v_a i_a + v_b i_b + v_c i_c \tag{6}$$

$$q = \frac{1}{\sqrt{3}}\left[(v_b - v_c)i_a + (v_c - v_a)i_b + (v_a - v_b)i_c\right] \tag{7}$$

It is naturally possible to estimate the power-source voltages by simply adding converter output voltage to the voltage drops in the interconnecting reactors. Rewriting $P$ and $q$ with the switching state of the converter, the three-phase line currents, the dc-bus voltage, and the inductance of the reactors, estimated values $\hat{P}$ and $\hat{q}$ can be derived as:

$$\hat{p} = L\left(\frac{di_a}{dt}i_a + \frac{di_b}{dt}i_b + \frac{di_c}{dt}i_c\right) + v_{dc}(S_a i_a + S_b i_b + S_c i_c) \tag{8}$$

$$\begin{aligned}\hat{q} &= \sqrt{3}L\left(\frac{di_a}{dt}i_c - \frac{di_c}{dt}i_a\right) \\ &-\frac{1}{\sqrt{3}}v_{dc}\left[(S_a(i_b - i_c) + S_b(i_c - i_a) + S_c(i_a - i_b))\right]\end{aligned} \tag{9}$$

As can be seen in (8) and (9), the estimating equations have to be changed according to the switching state of the converter, and both equations require the parameter L of the reactors. The parameter R can be practically neglected because the power dissipation in the resistance is much lower than the active power associated with the dc bus and the inductance of the reactors.

After estimating instantaneous active and reactive power by (8) and (9) respectively, the power voltage vector $\hat{v}$ can be estimated using the following equations:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (10.a)$$

$$\begin{bmatrix} \hat{v}_\alpha \\ \hat{v}_\beta \end{bmatrix} = \frac{1}{i_\alpha^{\,2} + i_\beta^{\,2}} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix} \qquad (10.b)$$

$$\begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} \hat{v}_\alpha \\ \hat{v}_\beta \end{bmatrix} \qquad (10.c)$$

## 4. PROPOSED FUZZY CONTROL SCHEME

Fig.3 (a) shows the block diagram of the proposed fuzzy logic control scheme of the three-phase PWM rectifier. The dc-bus voltage $v_{dc}$ is sensed and compared with a reference value $v_{dc}$*. The obtained error e(k)=$v_{dc}$*(k)-$v_{dc}$(k) and its incremental variation Δe(k)=e(k)-e(k-1) at the k$^{th}$ sampling instant are used as inputs for fuzzy controller. The output is the instantaneous active power $P^*$. The dc-bus voltage is controlled by adjusting the active power using fuzzy controller.

The main characteristics of the fuzzy control are the following:

- Seven fuzzy sets for each of the two inputs;
- Seven fuzzy sets for the output;
- Triangular membership function;
- Fuzzyfication using continuous universe of discourse;
- Implication using Mamdani's min operator;
- Defuzzyfication using height method.

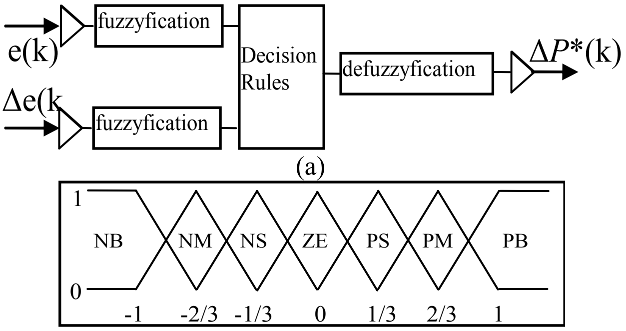
All fuzzy variables have the same membership functions. The fuzzy control has seven membership functions called from negative big (NB) to positive big (PB).

The fig. 3 (b) shows a unitary discussion universe which can be modified by simple gain on each variable. The idea of this partition is to simplify the number of calibration variables, reducing them to one gain for each variable:

GE for error; GD for change of error, and finally GU for $\Delta P^*$. The final output of the system is calculated as:

$P^*(k) = P^*(k-1) + GU.\Delta P^*(k)$.

According to the input fuzzy variables, the fuzzy logic controller determines the appropriate control output based on fuzzy rules. The fuzzy rules used in this proposed scheme are shown in TABLE II.



(a)

(b)

Fig.3. (a) Fuzzy control block. (b) Unitary discussion universe.

TABLE II
Fuzzy Control Table Showing Change in Control Output.

| | | e(k) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **NB** | **NM** | **NS** | **ZE** | **PS** | **PM** | **PB** |
| Δe(k) | **NB** | NB | NB | NB | NB | NM | NS | ZE |
| | **NM** | NB | NB | NB | NM | NS | ZE | PS |
| | **NS** | NB | NB | NM | NS | ZE | PS | PM |
| | **ZE** | NB | NM | NS | ZE | PS | PM | PB |
| | **PS** | NM | NS | ZE | PS | PM | PB | PB |
| | **PM** | NS | ZE | PS | PM | PB | PB | PB |
| | **PB** | ZE | PS | PM | PB | PB | PB | PB |

## 5. SIMULATION RESULTS

The parameters selected for the simulation studies of the three-phase PWM rectifier controlled by fuzzy logic and PI controller are shown in TABLE III.

TABLE III
Electrical Parameters of Power Circuit.

| | |
|---|---|
| Resistance of reactors R | 0.2 [Ω] |
| Inductance of reactors L | 11.5 [mH] |
| dc-bus capacitor C | 1 mF |
| Load resistance $R_L$ | 100[Ω] |
| Phase voltage V | 120 peak |
| Source voltage frequency f | 50 Hz |
| dc-bus voltage $v_{dc}$ | 250 V |

The active power command $P^*$ is adjusted using the fuzzy controller to control the dc-bus voltage in closed loop. According to the input signals $S_p$, $S_q$, and $\theta_n$ the optimum switching state $S_a$, $S_b$, and $S_c$ of the converter is selected using the switching table I. The simulation study has been performed with two main objectives in mind:

- Explaining and presenting the steady-state operation of the proposed DPC based on fuzzy controller with a purely sinusoidal and distorted supply line voltage;
- Presenting the dynamic performance of DPC based on fuzzy logic control.

Several tests were conducted to verify feasibility of the proposed technique. Fig.4 shows the simulated waveforms under unity power factor operation in the steady state for purely sinusoidal supply line voltage.

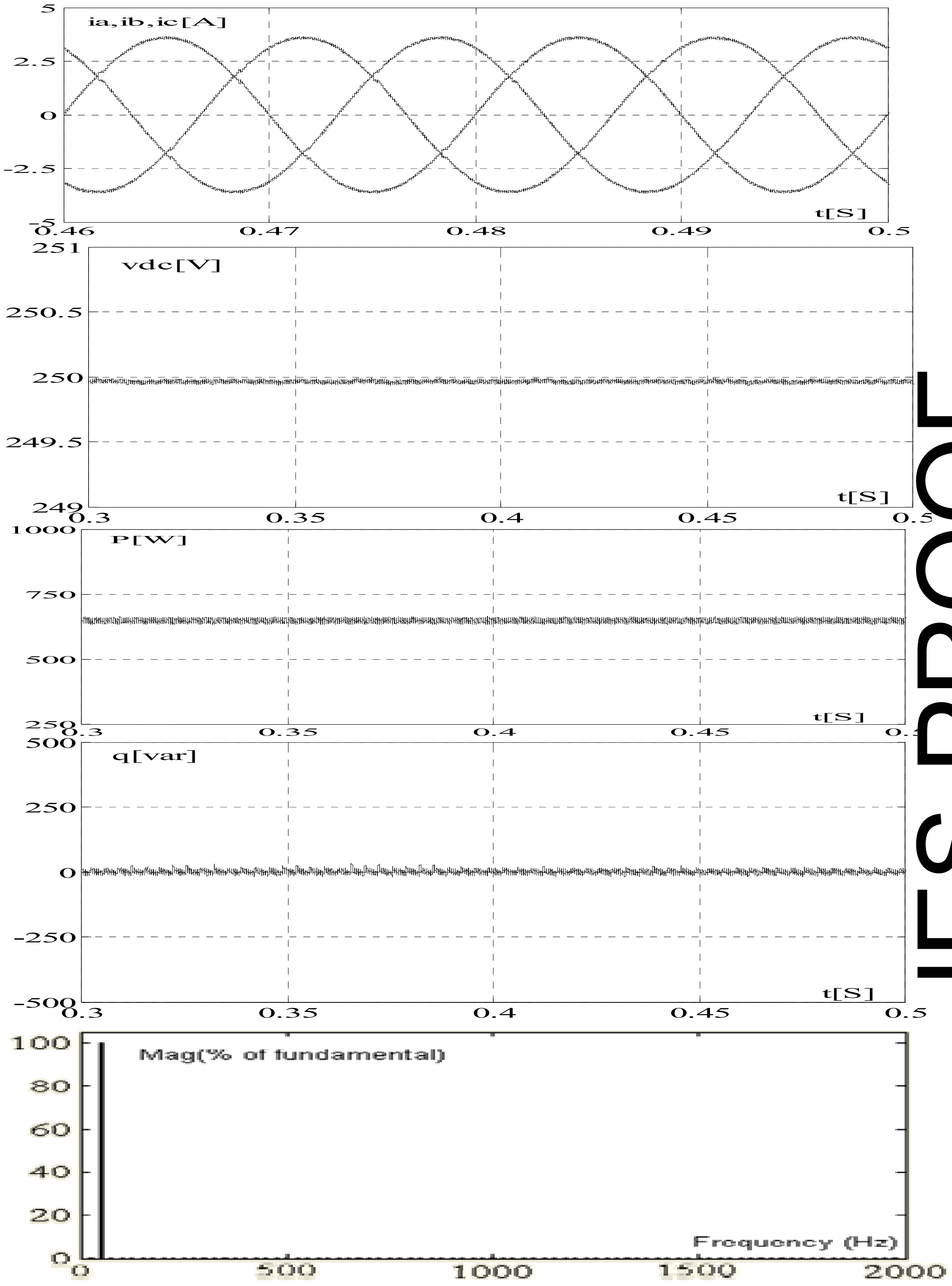


Fig.4 Simulated basic signal waveforms and line current harmonic spectrum under purely sinusoidal line voltage for $v_{dc}^*$=250V using fuzzy controller. From the top: line currents (THD=1%), output voltage, instantaneous active power, instantaneous reactive power (PF=0.999), and harmonic spectrum of line current.

From this figure, it can be seen that the line currents are very close to sine wave and in phase with the power-source voltages because the reactive power command $q^*$ is set to zero. The active power is constant on average (652.6 W). The reactive power is zero on average because of the unity power factor operation.

Fig.5 shows a result of a step response against the disturbance load power under the unity power factor operation. The load power was changed stepwise from 625 to 937.5 in this test. 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 output voltage is maintained close to its reference value. From Fig.5, it can be found that the active power control and the reactive power control are independent of each other.

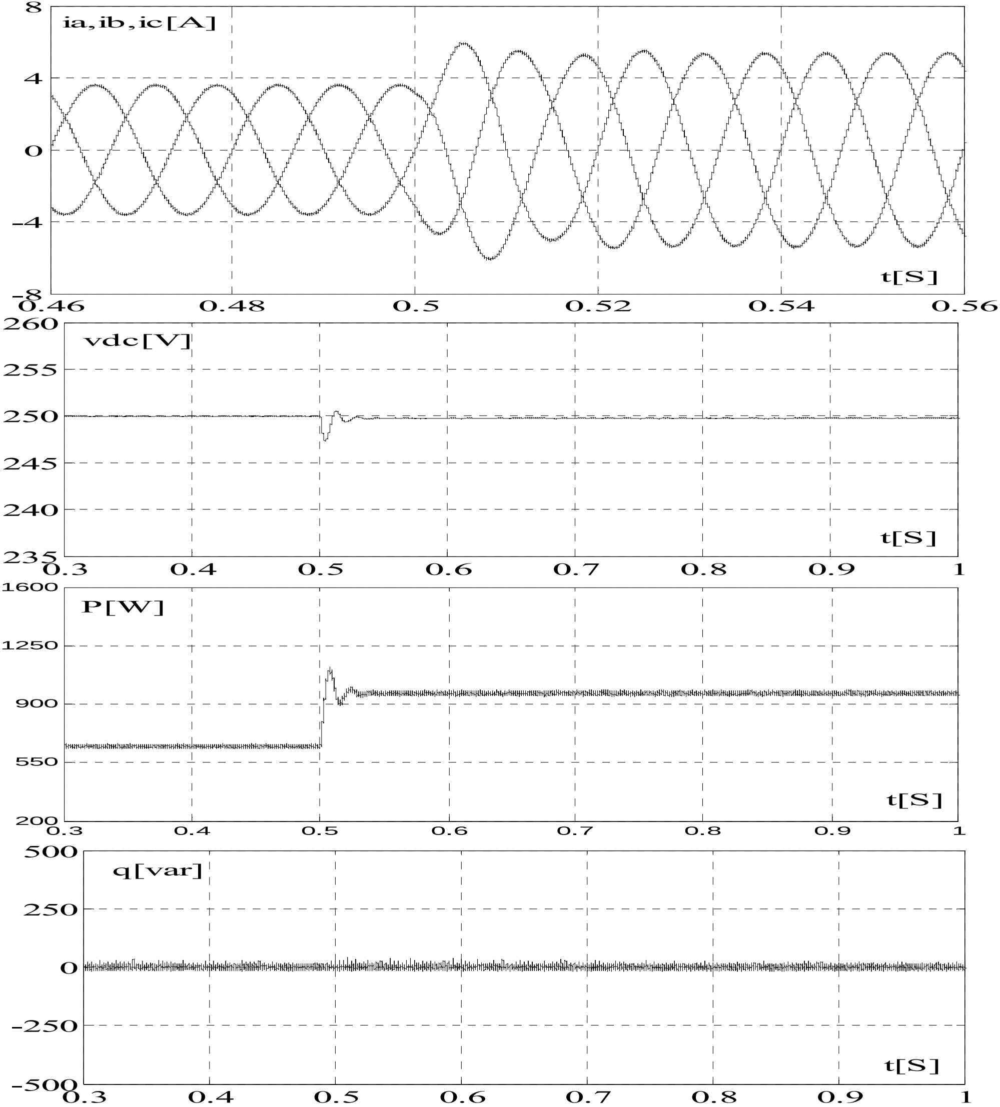


Fig. 5 Transient of the step change of the load, load increasing (50%) using fuzzy controller. From the top: line currents, output voltage, instantaneous active power, and instantaneous reactive power.

The dynamic behavior under a step change of $v_{dc}*$ is presented in Fig.6. After a short transient, the output voltage is maintained close to its new reference and the active power is maintained constant after a short transient. Reactive power is maintained zero.

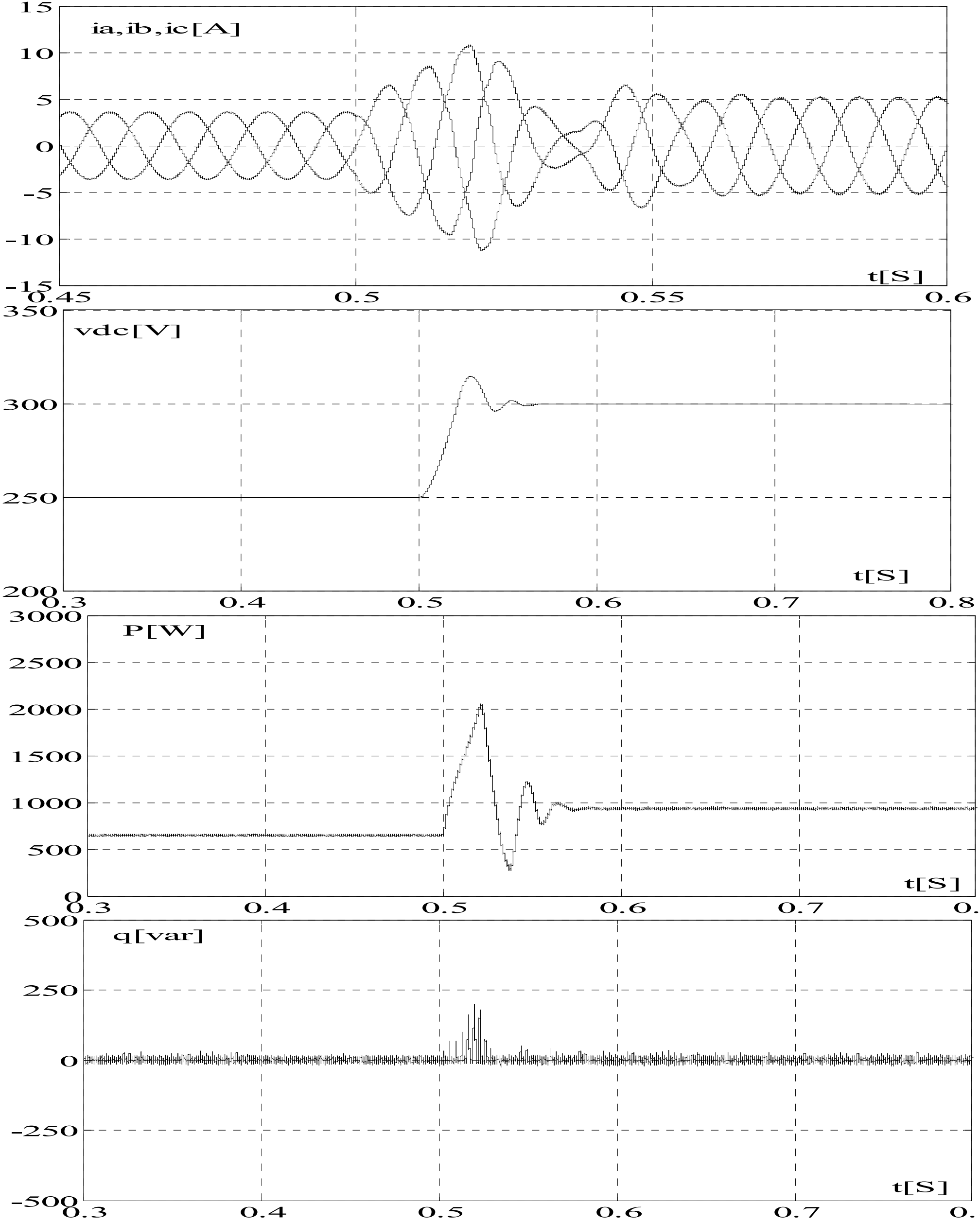


Fig. 6 Transient of the step change of the $v_{dc}*$, from 250V to 300V, using fuzzy controller. From the top: line currents, output voltage, instantaneous active power, and instantaneous reactive power.

Fig.7 shows waveforms in which the fifth harmonic component of 5% was intentionally superposed on the power-source voltages. In order to improve the total power factor, the line current should be controlled so that the active power and reactive power are maintained constant on average.

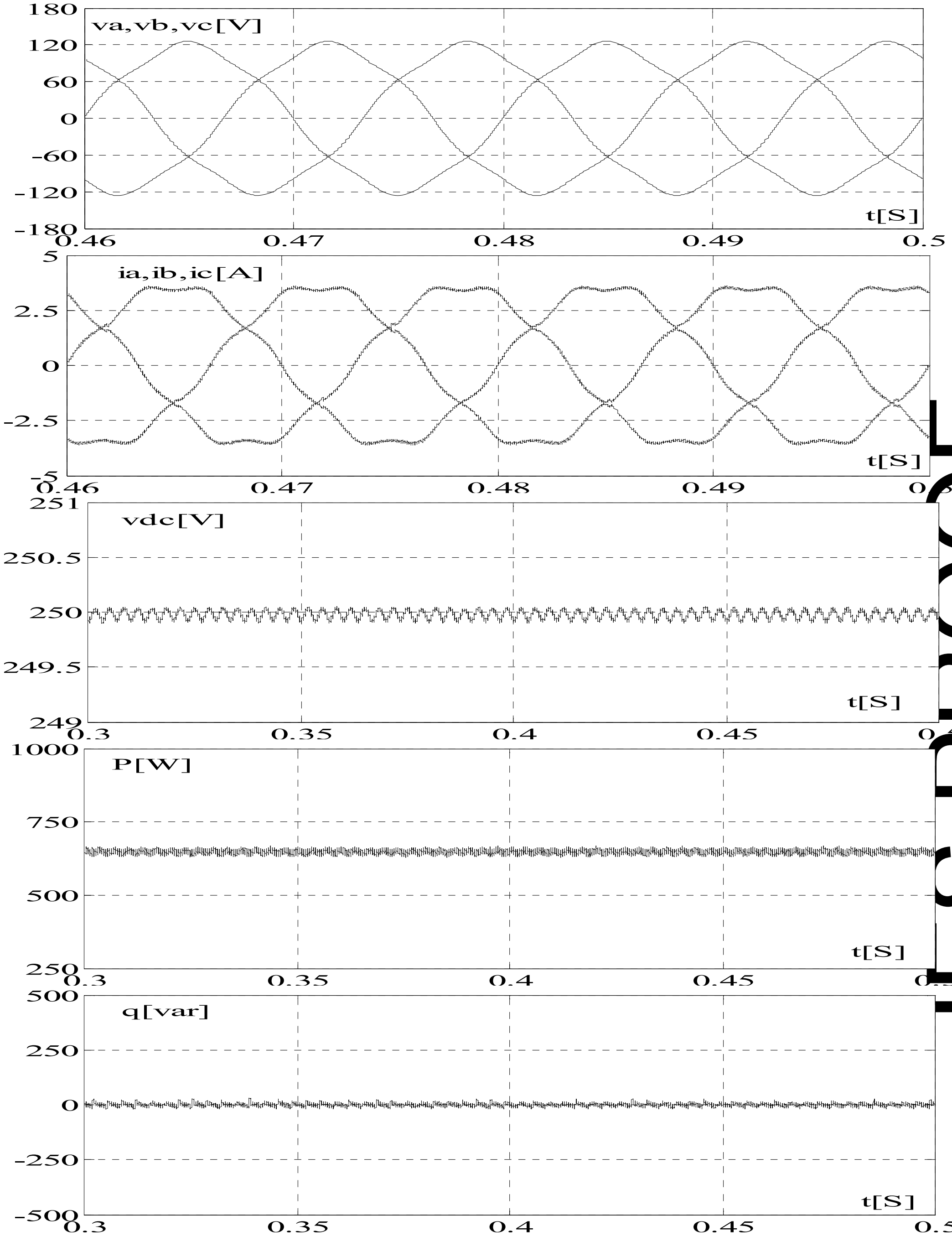


Fig. 7 waveforms under unity power factor operation when the fifth harmonic is superposed on power-source voltages.

The proposed method can control the power factor indirectly by changing the reactive power command *q**. Fig.8 and Fig.9 shows examples of the operation characteristics under lagging and leading power factor operations. In these tests, the reactive power command has been changed to +500 var or -500 var, and it is confirmed that the fuzzy controller can adjust the current phase indirectly with respect to the voltage through the reactive power command.

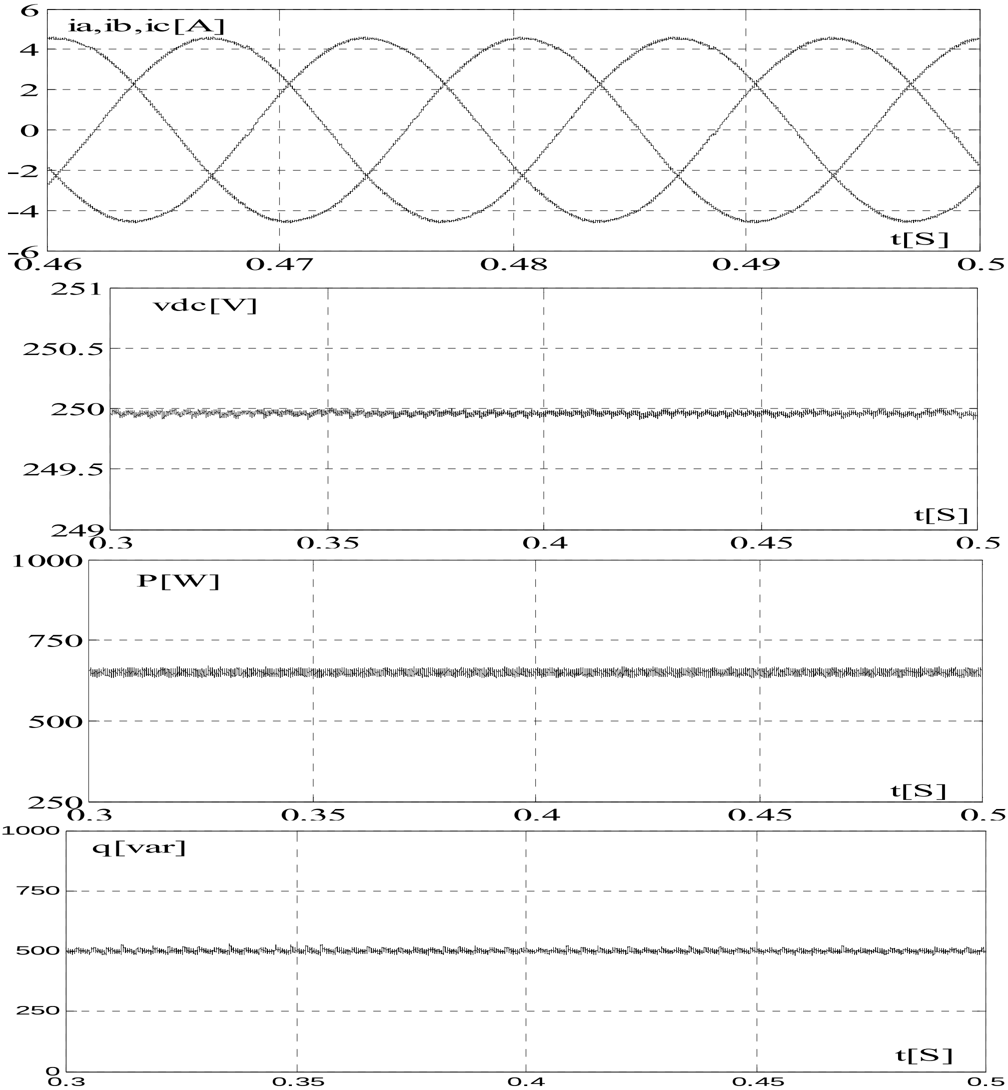


Fig. 8 waveforms under lagging power factor operation using fuzzy control *q**=+500 var.

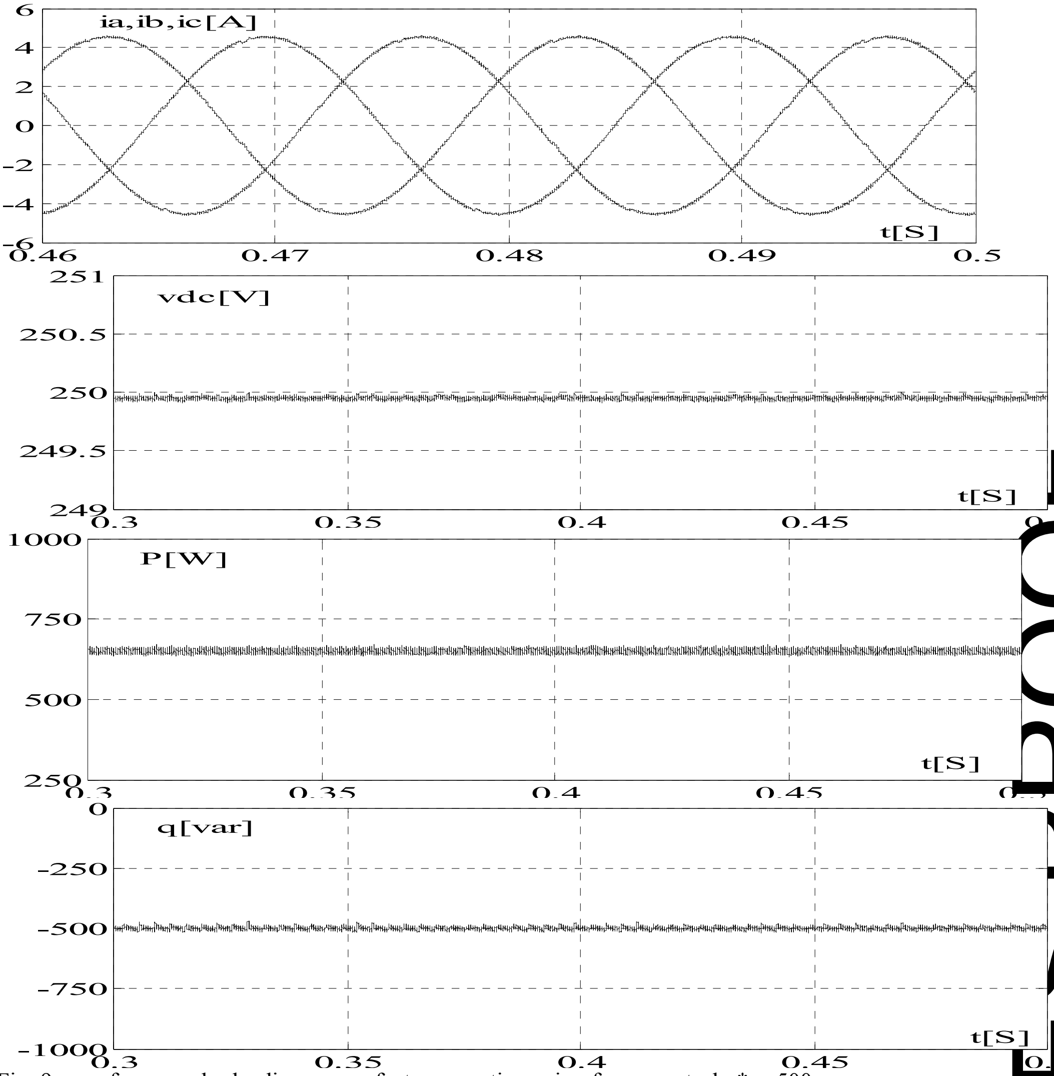


Fig. 9 waveforms under leading power factor operation using fuzzy control $q^*$= -500 var.

It is clear that the transient response in the line currents, the output voltage, and the active and reactive power is faster with the fuzzy control scheme. With fuzzy logic, the output voltage is recovered in less than 0.05s, but with conventional PI, the same situation takes more than 0.15s Fig.10 (a) and (b).

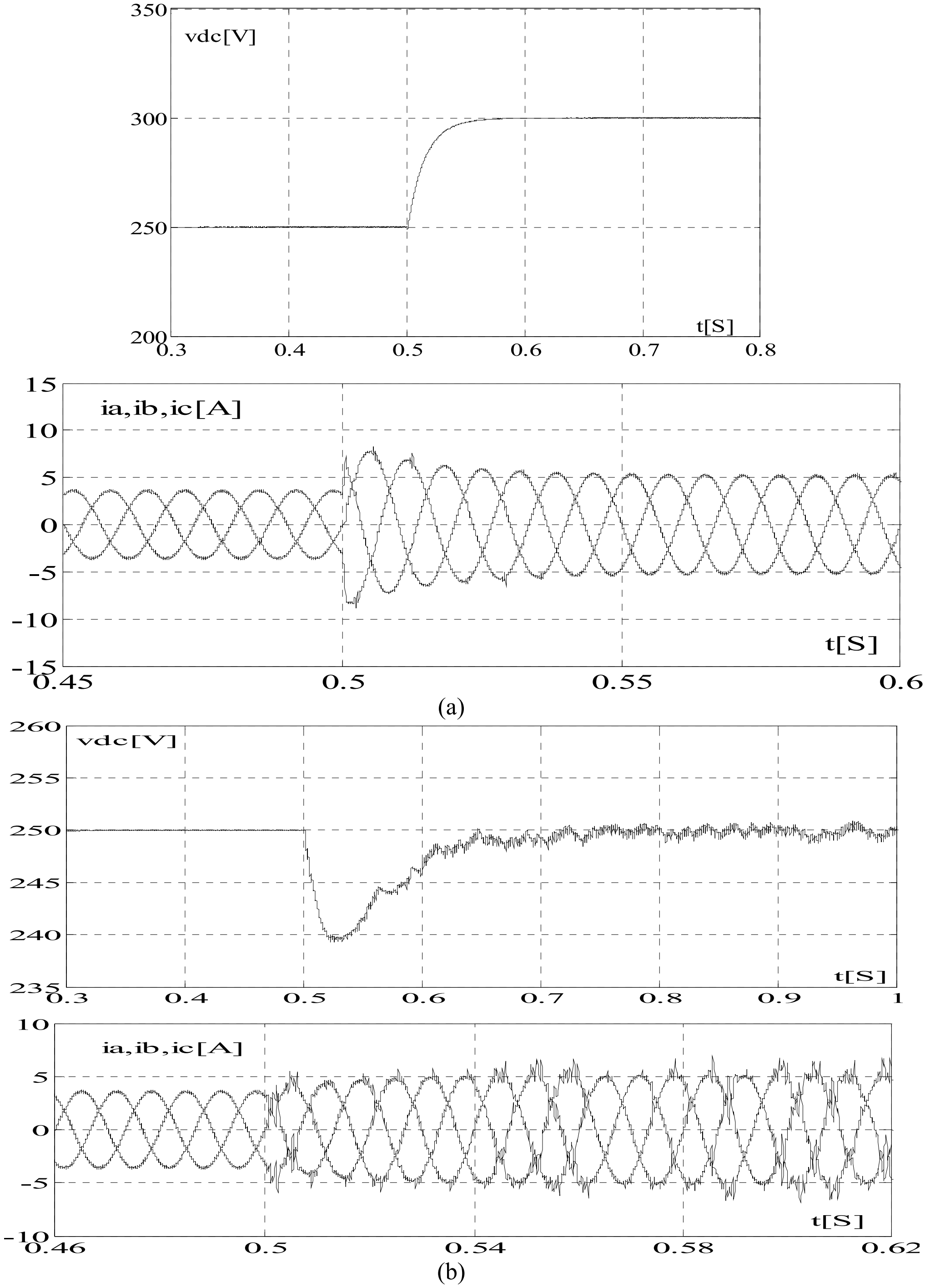
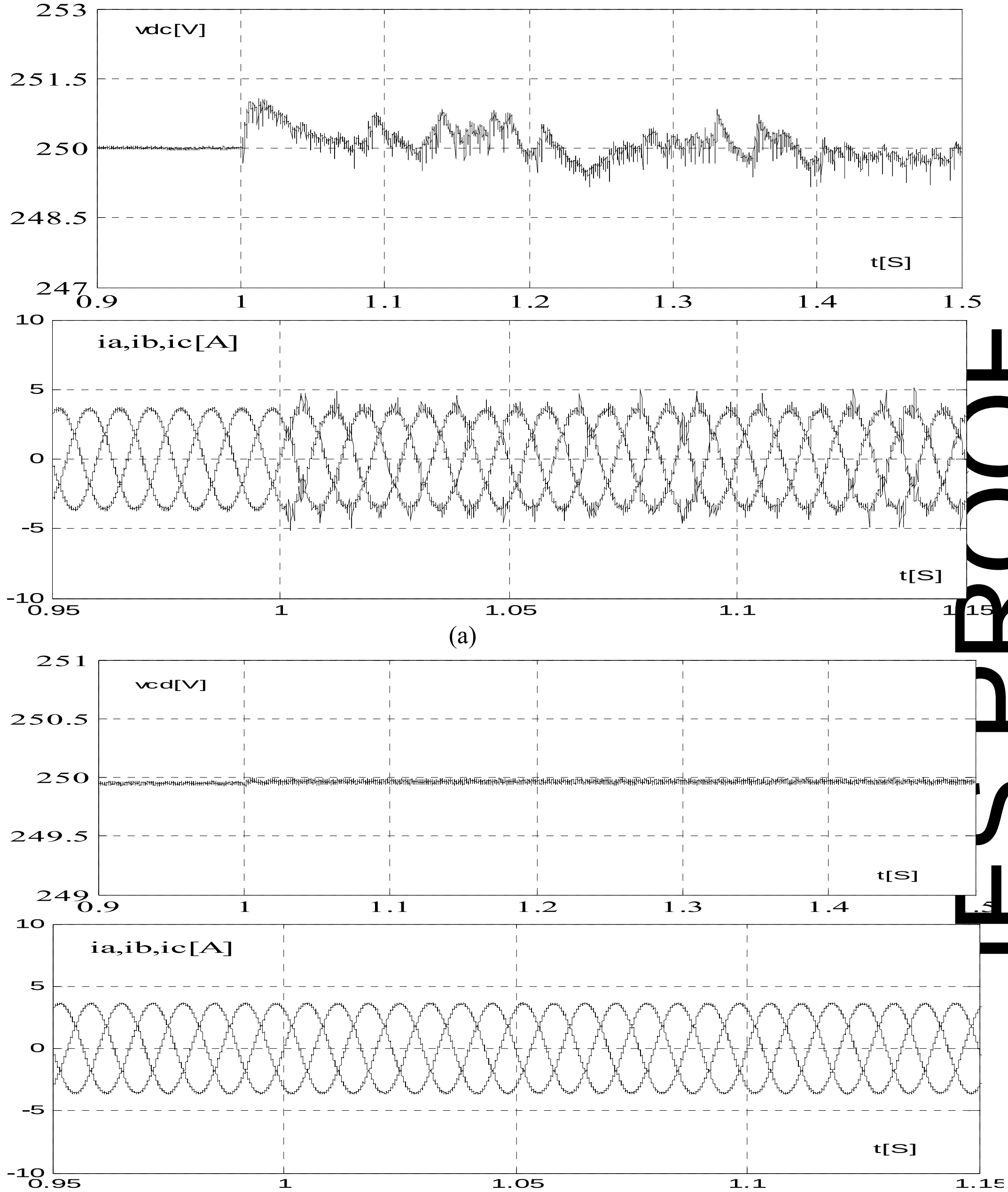


Fig.10 Transient response of the output voltage $v_{dc}$ and line currents with conventional PI controller for: (a) Step change of $v_{dc}$*, (b) Step change of the load, load increasing (50%).

The response of the system to the parameter variations is presented in Fig.11 (a) and (b) with PI and fuzzy controller respectively. In this test the dc-link capacitor is decreasing

(20%). It can be seen that the designed fuzzy controller is very robust to the parameter variations of the system. Line currents obtained by fuzzy control are very close to sine wave.



(a)

(b)

Fig.11 Transient response of the output voltage $v_{dc}$, and line currents for step change of dc-link capacitor (decreasing 20%).
(a) With conventional PI controller
(b) With fuzzy controller.

## 6. CONCLUSION

This paper has described a DPC based on fuzzy controller of three phase PWM rectifier to achieve unity power factor operation without power-source voltage sensors. The active and reactive power can be regulated directly by relay control of the power and a switching table. In this configuration, the errors between the power commands and the feedback signals are compared by the hysteresis elements, and the specific switching state of the converter is appropriately selected by the switching table, so that the errors can be restricted within the hysteresis bands. We observed from our simulation results that the DPC based on fuzzy logic controller guarantees a good regulation of the output voltage with a near unit power factor (PF=0.999, THD<2%) and decoupled active and reactive power control. This controller has a better transient response and steady state performance compared to a conventional PI controller.

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