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Comparison of PI and Fuzzy logic DC-Link Voltage Controller for DPC PWM-Rectifier

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Abstract: This paper treats direct power control (DPC) for three-phase PWM rectifiers using a new switching table, without line voltage sensors and the fuzzy logic theory. 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. These strategies are used to eliminate harmonics currents and consequently to reduce total harmonic distortion (THD) of the line current and improve the power factor with maintain the dc-bus voltage at the required level. Conventional PI and a designed fuzzy logic-based controller, in the dc-bus voltage control loop, have been used to provide active power command. A digital simulation, in Matlab/simulink, was carried. The steady-state and dynamic results illustrating the operation and performance of the proposed control scheme are presented. As a result, it was confirmed that the novel DPC is much better than the classical one. Simulation results show clearly the effectiveness of the adopted control strategies.

Keywords: Direct power control (DPC), fuzzy control, instantaneous active and reactive powers, PWM rectifier, PI controller, THD, voltage estimation.

Introduction

The increasing use of electronic devices in power electrical systems has led to more and more problems associated with distortion harmonics in electrical networks. Harmonic currents are mainly issued by non-linear loads based electronic power devices. These harmonics will generate harmonic voltages at different connection points to the network. Many of harmonic reduction method exist. These techniques based on passive components, mixing single and three-phase diode rectifiers, and power electronics techniques as: multi-pulse rectifiers, active filters and PWM rectifiers [1]. They compensate for disturbances due to a non-linear load in feeding back opposite phase on the network harmonics and reactive current drawn by the load so that the network is not only to provide a sinusoidal current in phase with the voltage. Performance of these methods, including the reduction of total distortion of source current and improved power factor, are not only related to the performance of the generation of harmonic current references, but also depend on the control strategy. Pulse Width modulation (PWM) rectifier are extensively used in AC variable speed drive, reactive compensation and active power filter for their high power factor, small total harmonic distortion (THD) systems, bidirectional power flow and fast dynamic response. Various control strategies were proposed in recent works for the PWM rectifier [2]. While they can reach the same total objective, such as a high power factor and sinusoidal current, but their principles vary. Particularly, the voltage orientation control (VOC) and virtual flux orientation control (VFOC), can guarantee a high dynamics and static performances by internal loops of current control [4]. These control strategies became very popular and consequently they are developed and improved. Final configuration and performances of the VOC technique depend largely on the quality of the current control strategy [3]. Other approach relies on instantaneous direct active and reactive power control, and is named direct power control (DPC) [2].

Appropriate switching states are selected for next switching table, based on hysteresis controller's outputs and the position of the line voltage space vector. However, high sampling frequency requirement is a main drawback of the switching table based direct power control scheme [4]. In more DPC shames for PWM rectifier, the active power exchange must be stable by insuring a DC voltage equal to its reference so that the PWM rectifier operates with a good efficiency. This can be carried out by using a control system able to regulate DC voltage. This paper presents a direct power control (DPC) of three phases PWM rectifier based on fuzzy logic control approach's; making 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. Although the reactive power command is close to zero to ensure unity power factor operation. Finally, the developed fuzzy controller is compared to classical PI controller. The simulation results shown that the proposed controller based on fuzzy logic control is introduced to improve the performances of the system behavior. Like a good rejection of impact load disturbance, a good dynamic behavior for dc output voltage regulation, for more reduction of THD and power ripple [5][6].

The PWM Rectifier Structure

The boost rectifier configuration is shown schematically in Fig. 1. The bridge circuit is constructed of six controllable power switches and anti-parallel diodes. The power network voltage is connected to the grid associated with a RL filter.

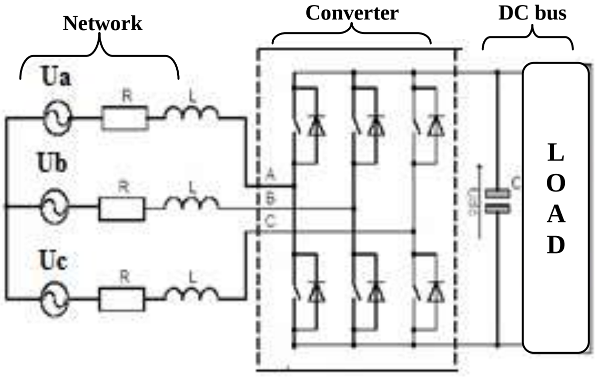

Figure 1. Structure of PWM rectifier

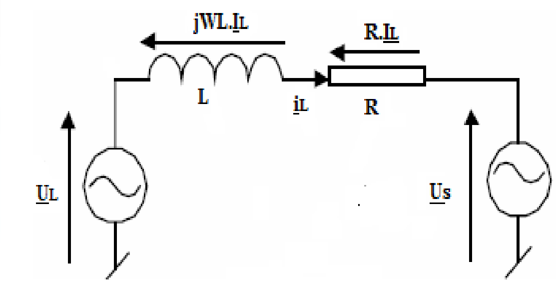

Figure 2. Single-phase equivalent circuit of the PWM rectifier

The voltage equation for this single phase circuit can be written as:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \qquad (1)$$

For the balanced three-phase voltage we can write PWM rectifier equation in stationary coordinates.

$$U_L = \begin{bmatrix} U_{L\alpha} \\ U_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 1/2 \\ 2 & \sqrt{\frac{2}{3}} \end{bmatrix} \begin{bmatrix} U_{ab} \\ U_{bc} \end{bmatrix} \qquad (2)$$

$$i_L = \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 2/3 & 0 \\ \frac{\sqrt{3}}{2} & \sqrt{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \qquad (3)$$

Also we can write PWM rectifier equation in synchronous rotating coordinates(R is neglected):

$$\begin{bmatrix} U_{Ld} \\ U_{Lq} \end{bmatrix} = L \frac{d}{dt} \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} + \omega \begin{bmatrix} -i_{Lq} \\ i_{Ld} \end{bmatrix} + \begin{bmatrix} U_{sd} \\ U_{sq} \end{bmatrix} \qquad (4)$$

The equation (4) can be transformed to vector form in synchronous d-q coordinates defining derivative of current as:

$$L\frac{di_{Ldq}}{dt} = U_{Ldq} - j\omega Li_{Ldq} - U_{sdq} \quad (5)$$

Voltages vector generated by the rectifier can be given by Table 1:

Table 1. Different switches configurations and the corresponding voltages vector

S_a	S_b	S_c	U_{sa}	U_{sb}	U_{sc}	$U_{s\alpha}$	$U_{s\beta}$	V_i
0	0	0	0	0	0	0	0	V_0
0	0	1	-Udc/3	-Udc/3	2Udc/3	-Udc/√6	-Udc/√2	V_5
0	1	0	-Udc/3	2Udc/3	-Udc/3	-Udc/√6	Udc/√2	V_3
0	1	1	-2Udc/3	Udc/3	Udc/3	-√2/3.Udc	0	V_4
1	0	0	2Udc/3	Udc/3	Udc/3	√2/3.Udc	0	V_1
1	0	1	Udc/3	-2Udc/3	Udc/3	Udc/√6	-Udc/√2	V_6
1	1	0	Udc/3	Udc/3	-2Udc/3	Udc/√6	Udc/√2	V_2
1	1	1	0	0	0	0	0	V_7

The vector representation of voltage vectors generated by the rectifier is illustrated in fig.3:

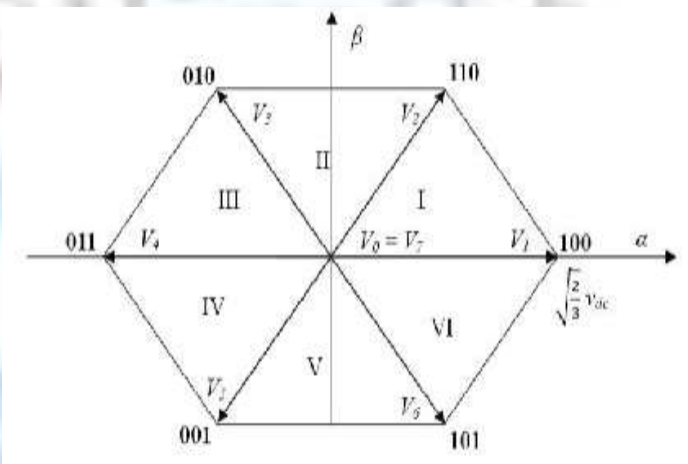

Figure 3. Voltage vectors generated by the rectifier

The Control Strategy Of The DPC

DPC of PWM rectifiers can be generally classified used two types of estimation:[2][7]

- Voltage estimation,
- Virtual flux estimation,

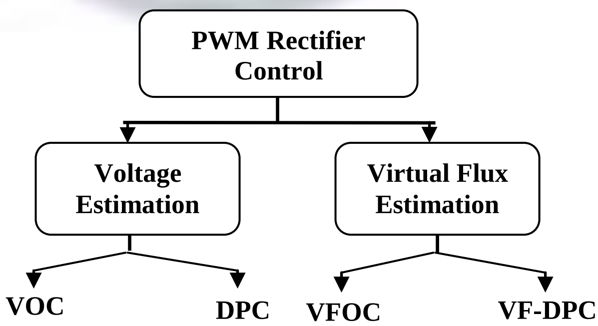

Figure 4. Different control strategies of a PWM rectifier

The DPC principle is based on a control vector selection according to a switching table found on the digitized errors Sp, Sq of instantaneous active and reactive powers, provided by two level hysteresis regulators, as well as on angular position of the estimated voltage vector. According to this position value, the plan (α -β) is divided into twelve sectors where one

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must associate at each sector a logical state of the rectifier. The reference of the active power is obtained by a PI controller of the DC voltage. In order to ensure a unit power-factor, the reactive power reference is chosen equal to zero. Hence the key point for implementing DPC strategies is a correct and a fast estimation of active and reactive line powers. Fig.5 shows the block diagram of the DPC system and load [8][9].

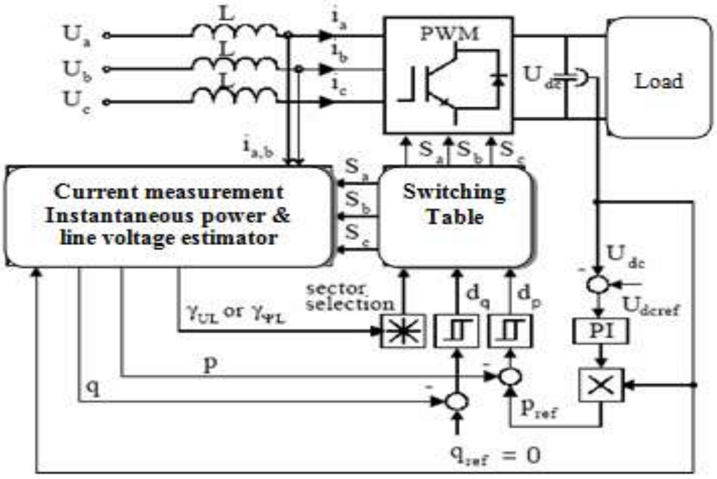


Figure 5. Direct power control method Block scheme

Reactive power is estimated by the equations 6, 7. In this equation i_a , i_b , i_c are the ac-line measured current and the S_a, S_b, S_c are the switching state of the converter. These two equations require knowledge of the line inductance L [9].

$$p = L\left(\frac{di_a}{dt}i_a + \frac{di_b}{dt}i_b + \frac{di_c}{dt}i_c\right) + U_{dc}\left(S_a i_a + S_b i_b + S_c i_c\right) \quad (6)$$

$$q = \sqrt{3}L\left(\frac{di_a}{dt}i_c - \frac{di_c}{dt}i_a\right) - \frac{1}{\sqrt{3}}U_{dc}\left[S_a\left(i_b - i_c\right) + S_b\left(i_c - i_a\right) + S_c\left(i_a - i_b\right)\right] \quad (7)$$

The ac-line current are measured and the values of the active and reactive power are estimated by equations.6,7 and then the line voltage can easily be calculated from the equation 8.

$$\begin{bmatrix} U_{l\alpha} \\ U_{l\beta} \end{bmatrix} = \frac{1}{i_{l\alpha}^2 + i_{l\beta}^2}\begin{bmatrix} i_{l\alpha} & -i_{l\beta} \\ i_{l\beta} & i_{l\alpha} \end{bmatrix} \quad (8)$$

Fig.6 shows the instantaneous active power, reactive power and ac voltage estimator block

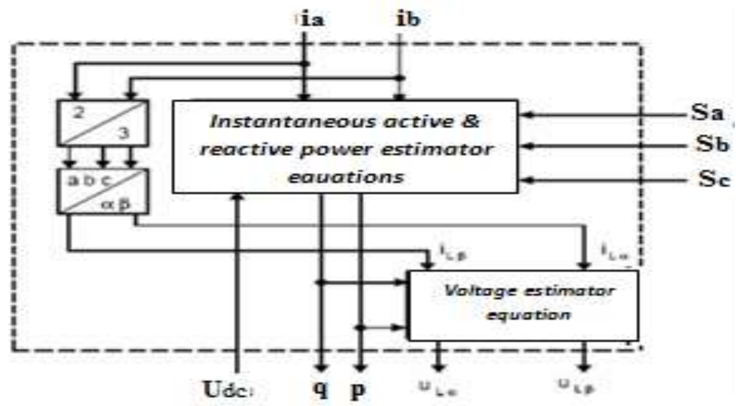


Figure 6. Instantaneous active and reactive power estimation

The knowledge of the estimated voltage sector is necessary to determine optimal switching states. Determination of the number sector is given by:

$$(n-2)\frac{\pi}{6} \prec \gamma_n \prec (n-1)\frac{\pi}{6} \quad (9)$$

Where: n=1,…,12

n indicate the sector number. It is instantaneously given by the voltage vector position ant is computed as follows:

$$\gamma = \tan^{-1}\left(\frac{U_{l\beta}}{U_{l\alpha}}\right) \tag{10}$$

Fig. 6 shows the 12sector voltage plane for switching table.

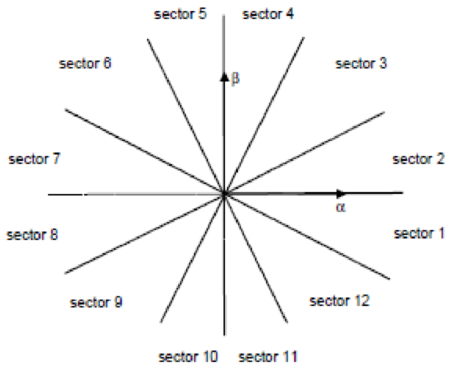


Figure 7. α-β plant divided into 12 sectors

In this system the active and reactive power is estimated at each time. The digitized output signals of the reactive and active power controller are defends as:

$$\begin{cases} p_{ref} - \hat{p} \succ h_p \rightarrow S_p = 1 \\ p_{ref} - \hat{p} \prec -h_p \rightarrow S_p = 0 \\ q_{ref} - \hat{q} \succ h_q \rightarrow S_q = 1 \\ q_{ref} - \hat{q} \prec -h_q \rightarrow S_q = 0 \end{cases} \tag{11}$$

Where *hp*, *hq* are the variations of the hysteresis regulators.

The digitized error signals S_P and S_q and the position γn of fundamental input voltage vector $U_{\alpha\beta}$ are inputs to the switching table in which every switching state (S_a, S_b, S_c) of the converter is stored, as shown in Table II. By using our own switching table, proposed in [10][11], the appropriate switching state of the converter can be selected in every specific moment according to the combination of the digitized input signals. The selected switching state allows the best restriction of both power tracking errors to achieve simultaneous control of p_h and q_h with good accuracy.

Table 2: Switching table

S_p	S_q	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_{12}
1	1	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
	0	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3
0	1	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
	0	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1

DC Voltage Regulation

In the proposed DPC scheme, magnitude of fundamental input currents is delivered from the outer proportional-integral (PI) dc-bus voltage controller and will be multiplied by the dc voltage to obtain the reference of the instantaneous active power.

To have unity power factor condition, reference reactive power must be equal to zero.

The regulation function is ensured by a PI corrector shown in the figure below:

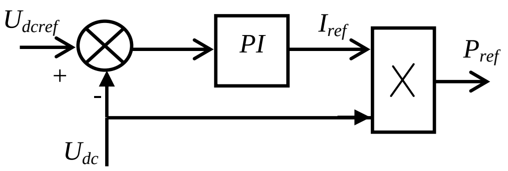


Figure 7. DC voltage regulation

Where K_p and K_i are the proportional and integral controller gains respectively.

To determine the parameters of the PI controller, we make the following mathematics development.

The relationship between the power absorbed by the capacitor and the terminal voltage can be written:

$$p_f = \frac{d}{dt}(\frac{1}{2}CU_{dc}^2) \quad (12)$$

Based the Laplace transform:

$$U_{dc}^2 = p_f \frac{2}{C.S} \quad (13)$$

The transfer function of the PI controller can be expressed by:

$$k_p + \frac{k_i}{S} = \frac{1+\tau S}{T_i S} \quad (14)$$

The transfer function of the closed loop system is given by:

$$F(S) = \frac{\omega_0^2(1+\tau)}{S^2 + 2\xi\omega_0 S + \omega_0^2} \quad (15)$$

With: $\omega_0 = \sqrt{\frac{2}{CT_i}}$ and: $\xi = \frac{\tau}{\sqrt{2CT_i}}$

We found: $k_p = \frac{\tau}{T_i}$ and: $k_i = \frac{1}{T_i}$

For a good performance of DC voltage control, in particular in the case of change of DC reference voltage level, the PI controller is replaced by a fuzzy controller.

Proposed Fuzzy Control Scheme

The principal scheme of the proposed fuzzy logic control is given by fig 8. [12]. The dc bus voltage U_{dc} is sensed and compared with a reference value U_{dcref} .the obtained error e(n)=U_{dcref} (n)-U_{dc}(n) and its incremental variation de(n)=e(n)-e(n-1) at the n^{th} sampling instant are used as inputs for fuzzy controller. The output is the instantaneous active P_{ref}. the dc bus voltage is controlled by adjusting the active power using fuzzy controller.

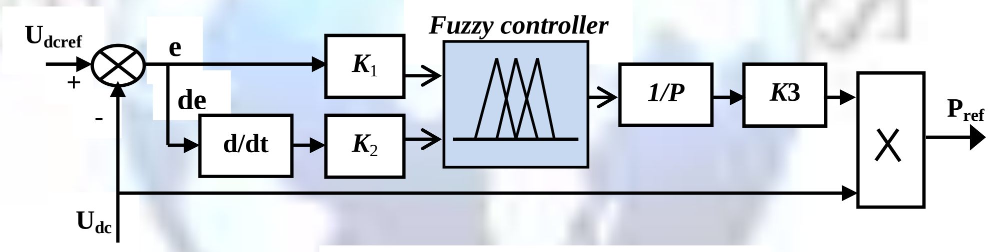


Figure 8. DC voltage fuzzy control

The fuzzy controllers allow the regulation of the DC bus voltage and generate the amplitude of the reference currents. The error of the DC bus voltage and its variation are used as inputs of the fuzzy process.
These two input variables are discredited with a sampling period T_s and normalized using the normalization gains (G_e) for error and ($G_{\Delta e}$) for the variation of the error they are defined by the following expressions.
The setting error in the DC bus voltage deviation is defined by:

$$e = U_{dcref} - U_{dc}$$

The incremental change in the setting error is defined by:

$$de(n) = e(n) - e(n-1)$$

The fuzzy controller output is considered the variation of the amplitude of the reference currents ΔI_M(n).
The amplitude of the reference currents for the n_{th} sample I_M (n) is obtained by adding the amplitude I_M (n-1). With the variation ΔI_M (n) as the following equation:

$$I_M(n) = I_M(n) + \Delta I_M(n)$$

The output is the instantaneous active power reference P_{ref}, the dc bus voltage is controlled by adjusting the active power using fuzzy controller.
The main characteristics of fuzzy controller are:

- Seven fuzzy sets for e(n), de(n), ΔI_M(n);
- Fuzzyfication using continuous universe of discourse;
- Implication using Mandani's operator;

- Defuzzyfication using height method;

The internal structure of fuzzy controller used is shown in Fig.9.

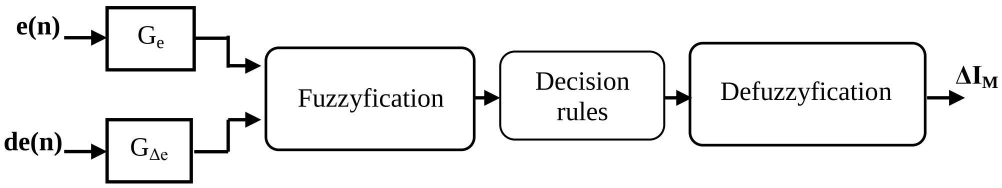


Figure 9. Internal structure of the fuzzy controller

For fuzzyfication, we used triangular membership functions for the error e (n), the variation of de(n) and output ΔIM (n), and we chose the seven fuzzy sets: NB negative big, NM negative medium, NS negative small, EZ zero, PS positive small, PM positive medium and PB positive big. [13]

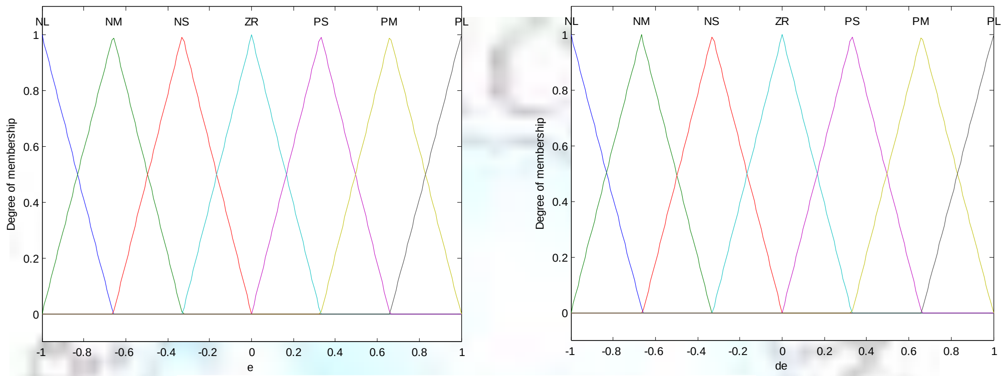


Figure.10: Membership functions of input

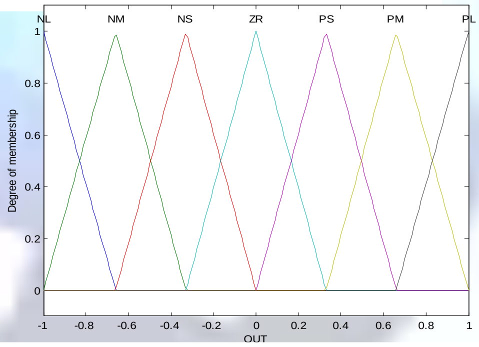


Figure.11: Membership functions of output

For the inference rules we have established are summarized in following Table:

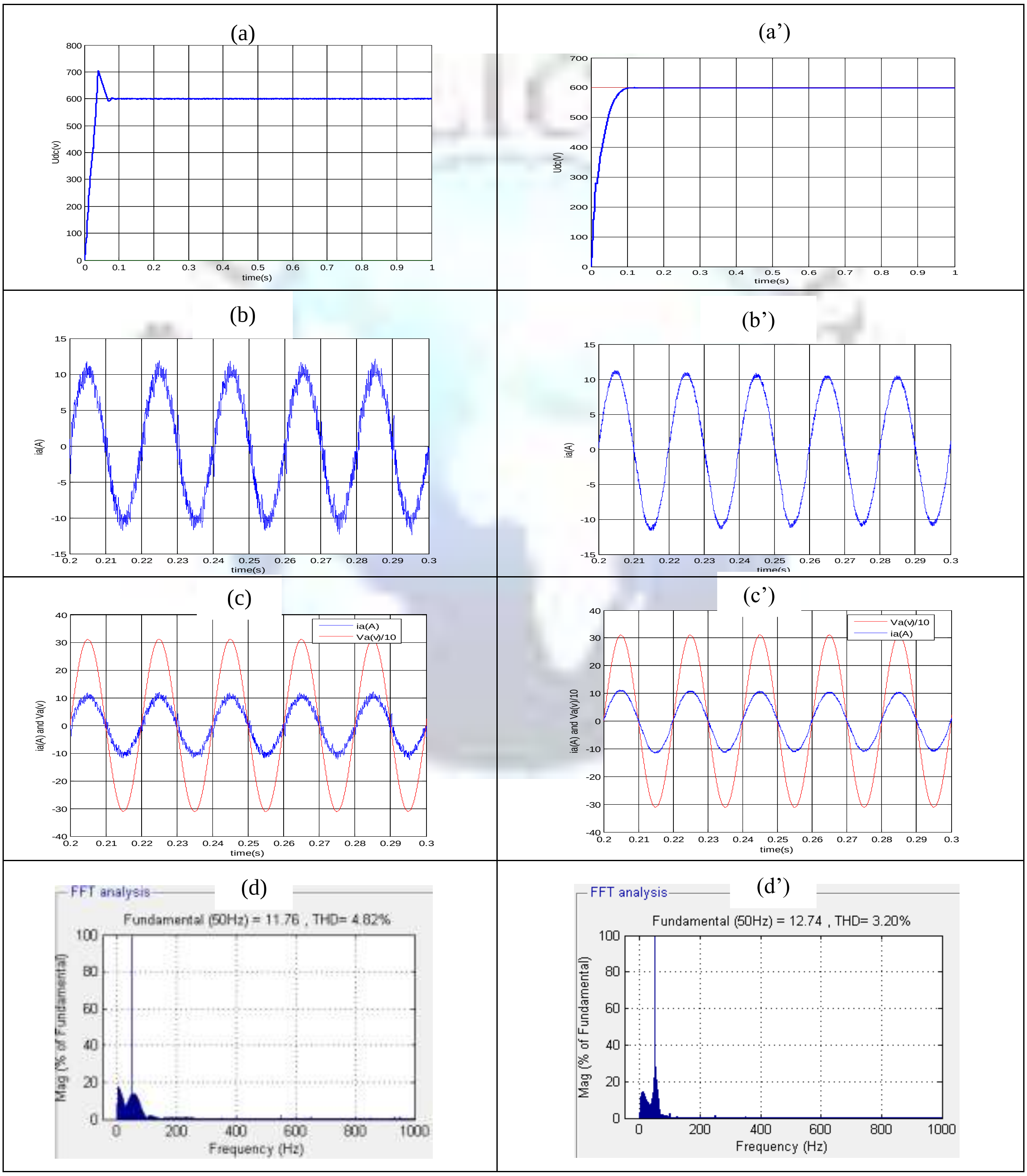
Table 3. The rules of the fuzzy controller

de\e	NB	NM	NS	EZ	PS	PM	PB
PB	EZ	PS	PM	PL	PL	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PS	NM	NS	EZ	PS	PM	PL	PL
EZ	NB	NM	NS	EZ	PS	PM	PL
NS	NB	NB	NM	NS	EZ	PS	PM
NM	NB	NB	NB	NM	NS	EZ	PS
NB	NB	NB	NB	NB	NM	NS	ZR

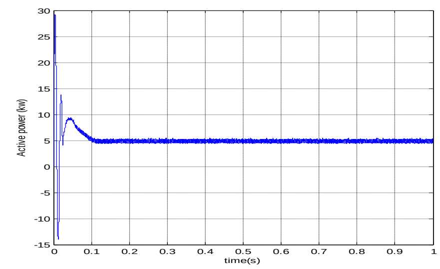
In order to confirm the effectiveness of the proposed DPC scheme and evaluate its performance under different input voltage conditions, a model of three-phase PWM rectifier, including the control system, has been simulated in Matlab/Simulink environment. Simulations have been carried out using the main electrical parameters of power circuit and control data showed in Table 4. Several tests were conducted to verify feasibility and performance of the fuzzy DPC scheme compared to the voltage estimate DPC with PI regulator.

Table 4. Electrical parameters of power circuit

Sample time T_s	10^{-05}s
Reactance of reactors R	0.3Ω
Inductance of reactors L	8mH
dc-bus capasitor C	2mF
Resistance load R_{load}	80Ω
Peak amplitude of line voltage	310V
Source voltage frequency	50Hz
DC voltage U_{dc}	600V



(e)



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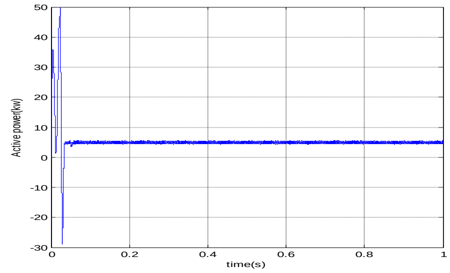


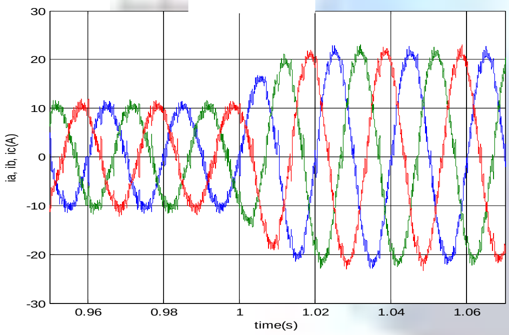
Figure 12: simulated results were obtained for purely sinusoidal supply line voltage and U_{dcref}=600V Using PI regulator, (a) output voltage, (b) line current, (c) line current with line voltage/10, (d) harmonic spectrum of line current and (e) instantaneous active power (kw).

Figure 13: simulated results were obtained for purely sinusoidal supply line voltage and U_{dcref}=600V Using Fuzzy logic controller, (a') output voltage, (b') line current, (c') line current with line voltage/10, (d') harmonic spectrum of line current and (e') instantaneous active power (kw).

The efficiency of the DC voltage fuzzy control is illustrated by fig.12 (a'). We can see that the system became more stable and robust compared to the PI regulator (fig 13. a). The system response is acceptable and does not present any overshoot. It's seen that the line current (fig 13.b) presented a ripples more than the line current (fig 12.b'). From the figure (13.c'), it can be seen that the line current are very close to sine wave and in phase with power source voltage because the reactive power q_{ref} is set to zero. The active power is constant on average (5Kw) (fig 13.e'). The THD of line current is reduced to 3.20% because of the unity power factor operation.

Figure 15 show a result of a step response against the disturbance load power under the unity power factor operation. The load power was changed step wise from 5kw to 10kw 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 (Tr=0.015s), the output voltage is maintained close to its reference value (figure 15.g') compared to the PI regulator (Tr=0.07s) (figure 14.g).

(f)



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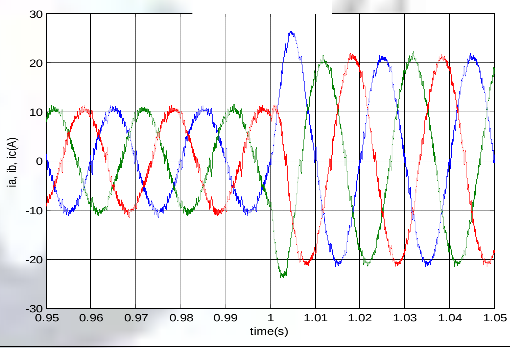
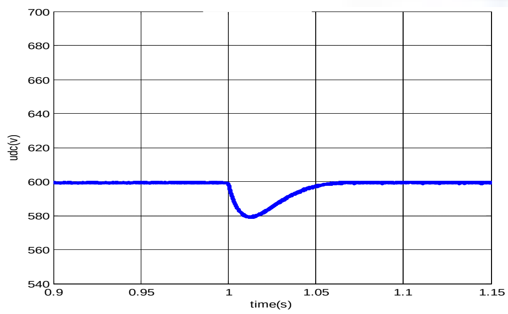
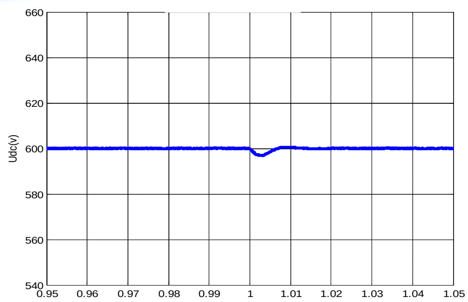


(g)



(g')



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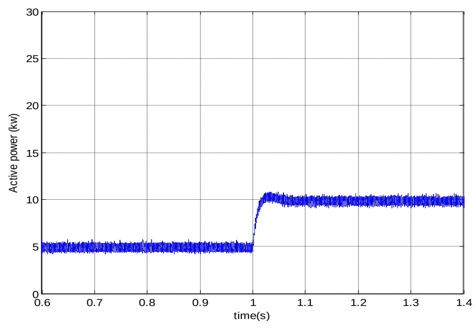

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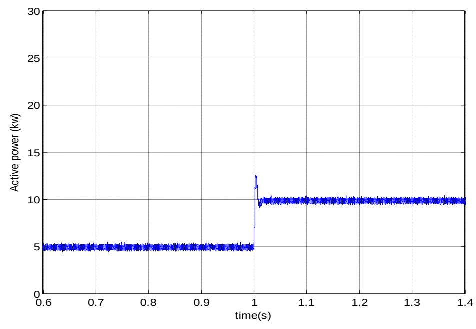
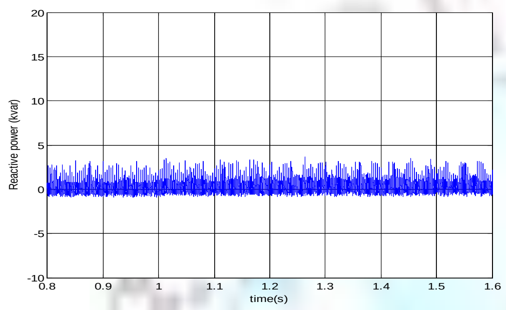


(i)



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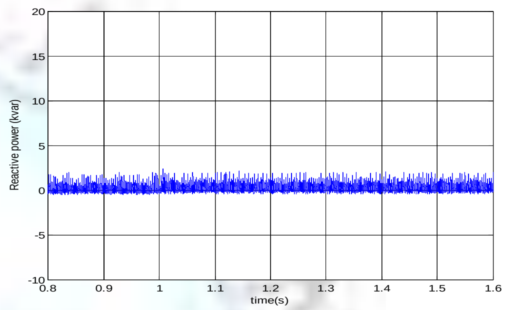
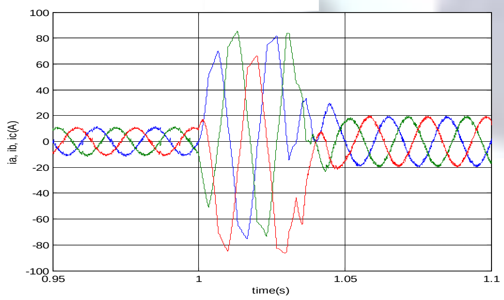


Figure 14: transient of the step change of the load, load increasing (50%) using PI regulator. From the top: (f) line current, (g) output voltage, (h) instantaneous active power, and (i) instantaneous reactive power.
Figure 15: transient of the step change of the load, load increasing (50%) using fuzzy controller. From the top: (f') line current, (g') output voltage, (h') instantaneous active power, and (i') instantaneous reactive power.

The dynamic behavior under a step change of U_{dc} is presented in figure 17. 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.

(j)



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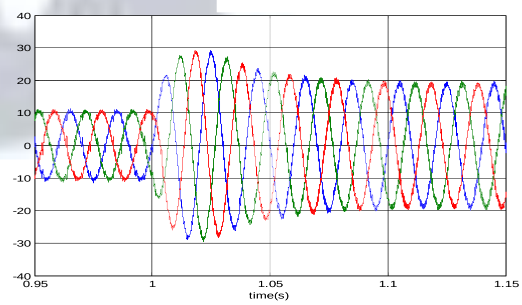
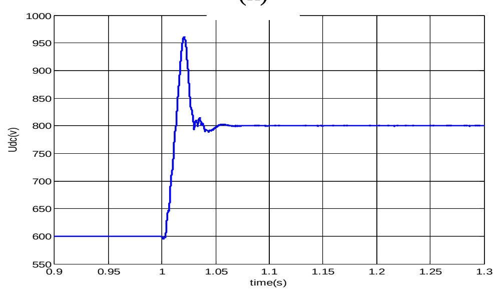
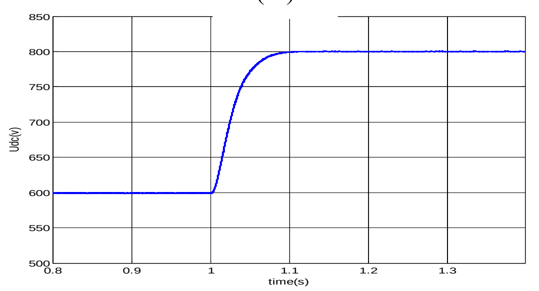


(k)



(k')



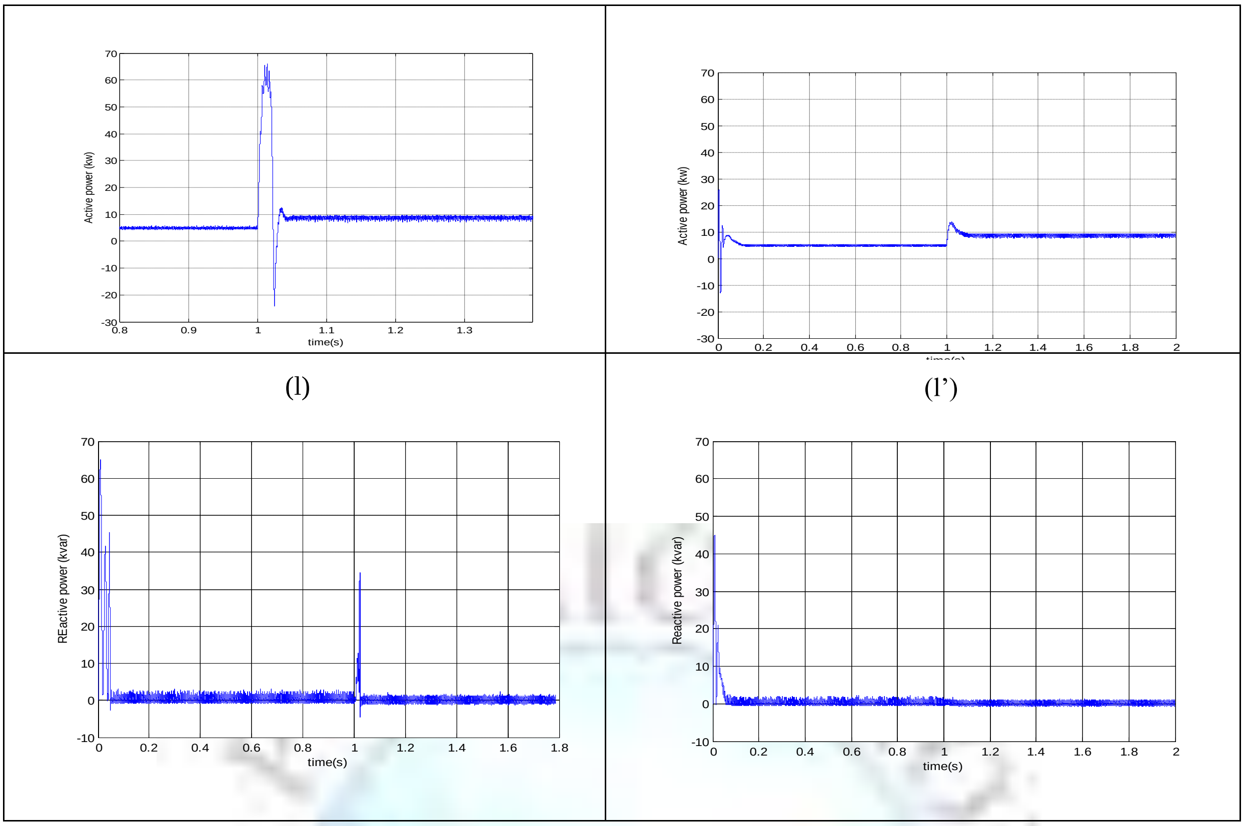


Figure 16: transient of the step change of the Udc from 600V to 800V, using PI regulator. From the top: (j) line current, (k) output voltage, (l) instantaneous active power, and (m) instantaneous reactive power.

Figure 17: transient of the step change of the Udc from 600V to 800V, using PI regulator. From the top: (j') line current, (k') output voltage, (l') instantaneous active power, and (m') instantaneous reactive power.

Fig.17 shows that when the DC voltage reaches the new reference value and the overshoot completely disappears (fig 17.k') compared to the figure (16.k), the active power and consequently the line current increase (fig 17.j'). In this case the power increase is limited (fig 17.m'), what avoids dangerous over currents for the system operation and we can see that the reactive power flow is small, what is very beneficial for the system performances.

The wave shape of the line current close to the sinusoid, and hence the THD (Total Harmonic Distortion) was reduced.

Conclusion / Results

This paper has presented the development and the implementation of a new direct power control (DPC) scheme for three-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. The active and reactive power can be regulated directly by relay control of the power and a switching table. Simulation results have proven excellent performance of the proposed DPC scheme which is much better than conventional DPC based on PI regulator. Even in both transient and steady states. Nearly sinusoidal waveforms of input currents are successfully achieved and guarantee a good regulation of the output voltage with a near unit power factor.

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