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Comparative Study of PI and Fuzzy DC Voltage Control for a DPC- PWM Rectifier

***Abstract**. This paper treats control strategies of a pulse width modulation (PWM) rectifier to eliminate harmonics currents and consequently to reduce total harmonic distortion of the line current and improve power factor. It is about the use of direct control principle to control instantaneous active and reactive powers. Such a technique is called direct power control (DPC). The principal idea of DPC was suggested initially by Ohnishi (1991) and developed then by Noguchi and Takahachi in 1998. This concept is similar to DTC applied to induction motors. A comparative study, concerning the DC voltage control, will be given in this study. It is about the use of a PI controller and a fuzzy logic one to ensure a stable active power exchange. A digital simulation, in Matlab/Simulink/SimPowerSystems and Fuzzy Logic Toolbox, was carried out and given in the end of this paper. The simulation results show clearly the supremacy of the technique adopted to control the DC voltage.*

***Streszczenie.** Analizowano różne strategie przekształtnika PWM umożliwiające eliminację prądów harmonicznych a w konsekcencjio poprawę współczynnika THD. Zastosowano technikę SPC – direct power control. Wykorzystano kontrolery PI i logiki rozmytej. Metody oceniono przeprowadzając symulacje. (**Analiza porównawcza sterownika napięcia DC w przekształtniku DPC-PWM**)*

Keywords: PWM rectifier, direct power control, voltage estimation, instantaneous active and reactive powers, fuzzy control.
Słowa kluczowe: przekształtnik PWM, DPC – direct power control

Introduction

Development in power electronics and the increase in power consumption as well as the flexibility in the use of semiconductors encouraged electro technologists to undertake significant associations of power static inverters to electric machines.

Generally, these devices represent nonlinear loads, which absorb a no sinusoidal current and behave like harmonics generators. Moreover, they consume sometimes reactive energy. Consequently, the wave shape of the source current loses its sinusoidal form and one also obtains a degradation of the power-factor.By this fact, electric power distributors are thus seen obliged to impose standards and to protect themselves from these disturbances.

Several control strategies were proposed in recent works for the PWM rectifier [1, 2, 3]. Although they can achieve the same total goal, such as a high power factor and sinusoidal current, but their principles differ. 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 [3, 4, 8, 11]. 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].

Another approach is based on instantaneous direct active and reactive power control, and is called direct power control (DPC) [2, 4]. Proper switching states are selected for next switching table, based on hysteresis controllers 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].

The first developed application of direct control was the stator flow control and the electromagnetic torque of an electric machine without any modulation block. Such structure was called *Direct Torque Control, DTC*. [5, 6].Then, Direct Power Control (DPC) was inspired from DTC and was proposed in [7]. In 2001, DPC was developed in [4] for controlling rectifiers connected to the network.In this case, active and reactive instantaneous powers represent the controlled variables.

DPC and VF-DPC are based on instantaneous control active and reactive powers [4]. In this control technique there is neither internal currents control loops, nor modulation block. In this control technique internal currents control loops and modulation block are eliminated. In this case, logical states of PWM rectifier are generated from a switching table based on instantaneous errors between estimated active and reactive powers and theirs reference values. These new techniques allow controlling the PWM rectifier without network voltages sensors.

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.

In this paper, two control systems of DC voltage are considered.In the first type, one will use a PI regulator whose proportional and integral actions offer to the system a minimal overshoot and a good response time.In the second type of control, human knowledge is introduced to improve the performances of the system behavior.

PWM rectifier structure [13, 14]

The power circuit of the PWM rectifier contains a bridge of six power transistors with anti-parallel diodes, which is used to carry out the PWM generation as well as the power bidirectional conversion.

The converter is supplied by a voltage source in series with an inductance and a resistance, which model the network. Generally, the network inductance is insufficient. To attenuate the ripples due to the switching operation of the PWM rectifier, a series filter having a more significant inductance is needed. A load and a 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.

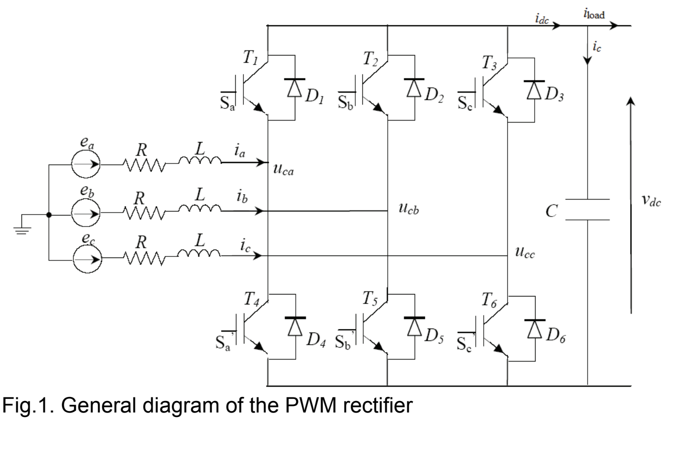

Fig.1. General diagram of the PWM rectifier

Logical states impose rectifier input voltages and check:

$$(1)\qquad \begin{cases} u_{ca} = S_a . v_{dc} \\ u_{cb} = S_b . v_{dc} \\ u_{cc} = S_c . v_{dc} \end{cases}$$

Thus the operation principle of the rectifier is illustrated by the following matrix system:

$$(2)\qquad \begin{bmatrix} u_{ca} \\ u_{cb} \\ u_{cc} \end{bmatrix} = v_{dc} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

The AC side can be modeled by the following equations:

$$(3)\qquad \begin{cases} u_{ca} = e_a - Ri_a - L\frac{di_a}{dt} \\ u_{cb} = e_b - Ri_b - L\frac{di_b}{dt} \\ u_{cc} = e_a - Ri_c - L\frac{di_c}{dt} \end{cases}$$

AC currents i_a, i_b and i_c are generated by voltage drops at impedances network boundaries (e_a-u_{ca}), (e_b-u_{cb}) and (e_c-u_{cc}), and then these currents will be cut out through the switches to provide the D.C. current i_{dc} such as:

$$(4)\qquad i_{dc} = S_a i_a + S_b i_b + S_c i_c$$

The same current charges the capacity in parallel with the load, therefore one can express it in another form:

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

Table.1 Different switches configurations and the corresponding voltages vector

S_c	S_b	S_a	u_{ca}	u_{cb}	u_{cc}	$u_{c\alpha}$	$u_{c\beta}$	V_i
0	0	0	0	0	0	0	0	V_0
0	0	1	$\frac{-v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	$\frac{2v_{dc}}{3}$	$\frac{-v_{dc}}{\sqrt{6}}$	$\frac{-v_{dc}}{\sqrt{2}}$	V_5
0	1	0	$\frac{-v_{dc}}{3}$	$\frac{2v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	$\frac{-v_{dc}}{\sqrt{6}}$	$\frac{v_{dc}}{\sqrt{2}}$	V_3
0	1	1	$\frac{-2v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$-\sqrt{\frac{2}{3}}v_{dc}$	0	V_4
1	0	0	$\frac{2v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\sqrt{\frac{2}{3}}v_{dc}$	0	V_1
1	0	1	$\frac{v_{dc}}{3}$	$\frac{-2v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{\sqrt{6}}$	$\frac{-v_{dc}}{\sqrt{2}}$	V_6
1	1	0	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{-2v_{dc}}{3}$	$\frac{v_{dc}}{\sqrt{6}}$	$\frac{v_{dc}}{\sqrt{2}}$	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.2:

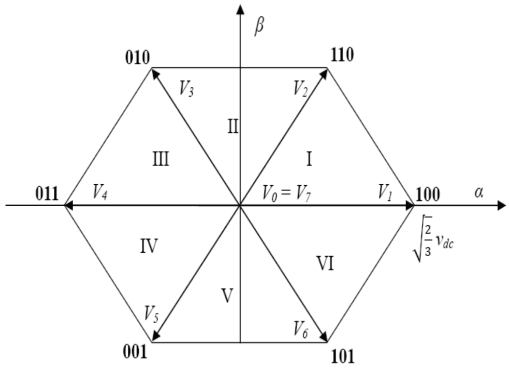

Fig.2. Voltage vectors generated by the rectifier

DPC strategy

DPC of PWM rectifiers can be generally classified used two types of estimation:[2, 11]

- Voltage estimation,
- Virtual flux estimation,

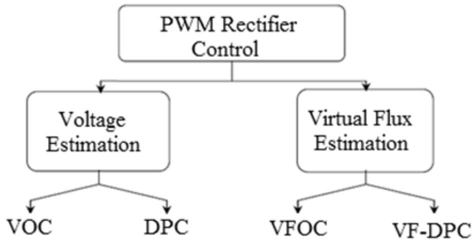

Fig.3. Different control strategies of a PWM rectifier

DPC principle is based on a control vector selection according to a switching table found on the digitized errors S_p, S_q 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 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.

DPC based on voltage estimation:

The estimation of instantaneous active and reactive powers is carried out by:

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

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

Line voltage estimation is carried out to know the line voltage vector position, what will allow us to compute the sector number.

The line voltage can be estimated by the following equation:

$$(8)\qquad \begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix}$$

The knowledge of the estimated voltage sector is necessary to determine optimal switching states.

Determination of the number sector is given by:

$$(9)\qquad (n-2)\frac{\pi}{6} < \gamma_n < (n-1)\frac{\pi}{6}$$

Where n=1,…,12

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

$$(10)\qquad \hat{\theta} = arct\left(\frac{\hat{e}_\beta}{\hat{e}_\alpha}\right)$$

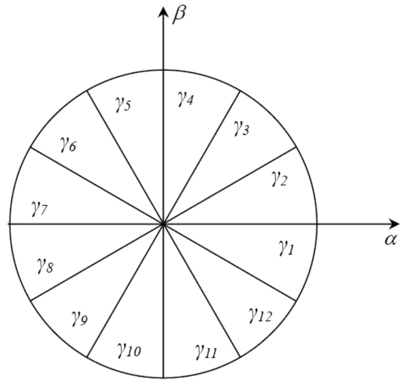

Fig.5. α-β plant divided into 12 sectors

The outputs hysteresis regulators given by the boolean variables S_p and S_q, indicate higher or lower limits of powers errors according to the below logic:

$$(11) \quad \begin{cases} p_{ref} - \hat{p} > h_p & \Rightarrow \quad S_p = 1 \\ p_{ref} - \hat{p} < -h_p & \Rightarrow \quad S_p = 0 \\ q_{ref} - \hat{q} > h_q & \Rightarrow \quad S_q = 1 \\ q_{ref} - \hat{q} < -h_q & \Rightarrow \quad S_q = 0 \end{cases}$$

where h_p, h_q are the variations of the hysteresis regulators.

By neglecting line voltage variations [9, 10], dynamics of active and reactive power can be given as follows:

$$(12) \quad \frac{dp}{dt} = \frac{1}{L}\left(e_\alpha^2 + e_\beta^2\right) - \frac{1}{L}\left(e_\alpha . u_{c\alpha} + e_\beta . u_{c\beta}\right)$$

$$(13) \quad \frac{dq}{dt} = \frac{1}{L}\left(e_\alpha . u_{c\beta} - e_\beta . u_{c\alpha}\right)$$

Logical states of the rectifier switches are generated basing on the switching table illustrated by Table.2.

Table.2 Switching table

S_p	S_q	γ1	γ2	γ3	γ4	γ5	γ6	γ7	γ8	γ9	γ10	γ11	γ12
1	0	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
1	1	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2
0	0	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	1	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

The corrector in the external control loop of the PWM rectifier is used to regulate DC side voltage and to generate magnitude of the reference line current witch 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:

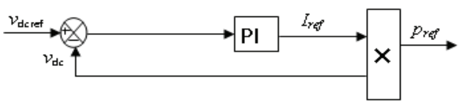

Fig.6. DC voltage regulation

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

To have a good performance of DC voltage control, especially in the case of reference DC voltage step variation, the PI corrector will be replaced by a fuzzy regulator.

The principal scheme of this control is given by: [12]

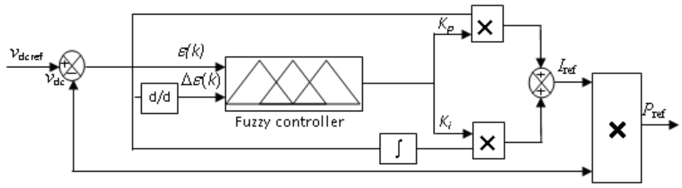

Fig.7. DC voltage fuzzy control

The new control structure of the DC voltage preserves the same model adopted when the PI regulator was used. These parameters are adjusted in real time according to the disturbance which increases.It is a question of associating the fuzzy regulator output to proportional and integral actions of the control signal.

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:

$$(14) \quad \varepsilon(k) = v_{dcref}(k) - v_{dc}(k)$$

$$(15) \quad \Delta\varepsilon(k) = \varepsilon(k) - \varepsilon(k-1)$$

Membership functions representing input and output variables are given by fig.8:

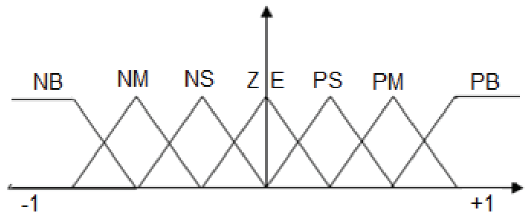

Fig.8. Membership functions of input and output variables

NB: Negative Big; NM: Negative Medium; NS: Negative Small; ZE: Zero; PB: Positive Big; PM: Positive Medium; PS: Positive Small;

Fuzzy rules are gathered in an inference matrix shown in Table.3:

Table.3. Matrix inference of the fuzzy controller

K_p/K_i		$\varepsilon = V_{dcref} - V_{dc}$						
		NB	NM	NS	ZE	PS	PM	PB
$\Delta\varepsilon$	NB	PB	PB	PB	PM	PM	PS	ZE
	NM	PB	PM	PM	PM	PS	ZE	NS
	NS	PB	PM	PS	PS	ZE	NS	NM
	ZE	PM	PM	PS	ZE	NS	NM	NM
	PS	PM	PS	ZE	NS	NS	NM	NB
	PM	PS	ZE	NS	NM	NM	NM	NB
	PB	ZE	NS	NM	NM	NB	NB	NB

Simulation and discussion

To validate the effectiveness of the control strategy studied in this paper, a digital simulation was carried out under MATLAB/SIMULINK environment.

The DC voltage control system is tested as well as the DPC method following a DC voltage step variation occurred at *t*=0.5s from 380V to 470V.

The effectiveness of the DC voltage fuzzy control is illustrated by fig.9. We can see that the system became more stable and more robust than when the PI regulator was used. In this figure the overshoot completely disappears and the response time is reduced

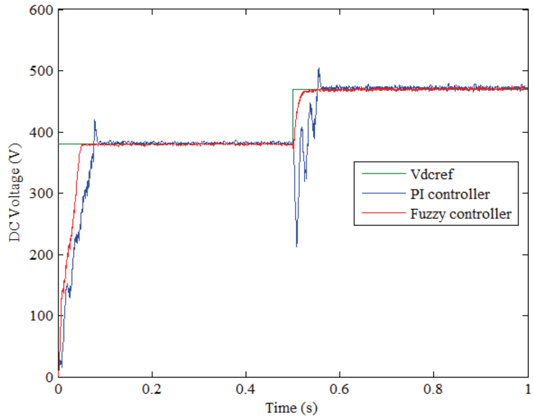

Fig.9. Control system step response (V_{dcref}=380 to 470 V)

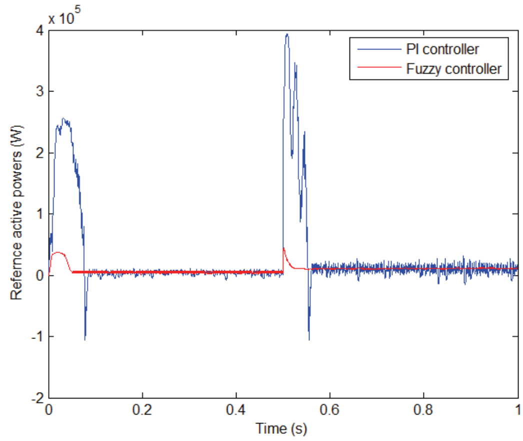

Fig.10. Reference instantaneous active power

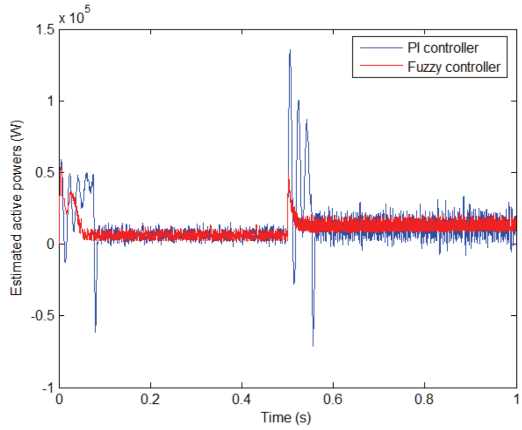

Fig.11. Estimated instantaneous active power

Fig.11 show that when the DC voltage reaches the new reference value, the active power and consequently the line current increase. For the fuzzy controller, the power increase is limited, what avoids dangerous overcurrents for the system operation.

In fig. 12, at the moment of DC step variation reactive power is sensibly reduced when a fuzzy regulator was used.

The line voltage and curent are almost in phase (see fig.13), and thus the power-factor is almost equal to 1. In the case of the fuzzy regulator, the wave shape of the line current close to the sinusoid, and hence the THD (Total Harmonic Distortion) was reduced.

In order to maintain the continuous bus charged, the DC voltage variation involves a reference variation in the instantaneous active power. Fig.10 shows that the DPC technique responds very quickly with regard to the power reference variation.

The system parameters studied in this article are given in Table.4.

Table.4 System parameters

R	88mΩ
L	3.127mH
C	1mF
R_{load}	100Ω
Peak amplitude of line voltage	200V
Source voltage frequency	50Hz
DC voltage V_{dcref}	380V

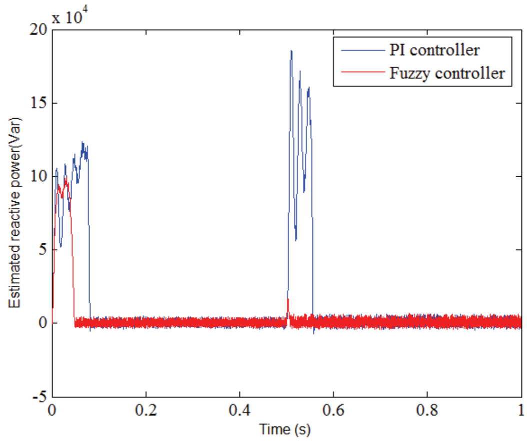

Fig.12. Estimated instantaneous reactive power

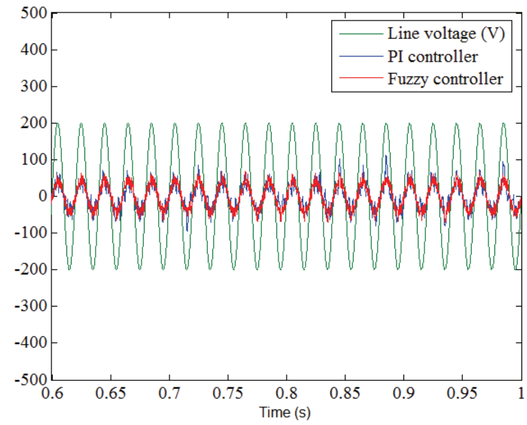

Fig.13. Line current in phase with line voltage after DC voltage step variation

Conclusion

In this article we presented a new control strategy for a PWM rectifier. It concerns the use of the direct power control principle. The advantage of the DPC method is to reduce the number of sensors used, and to offer a fast power response following a disturbance.Two techniques of DC voltage control were adopted in this study.All the simulation results obtained showed that the fuzzy controller improves the system performances compared to the PI controller.

These improvements affect the performances of the system response on the DC side (overshoot and response time), as well as the power-factor and the THD of the line current.

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