Fuzzy Logic Controller for DC link voltage regulation of a PWM rectifier.

Ruben Peña
Department of Electrical Engineering

University of Magallanes
Casilla 113-D. Punta Arenas
Chile
rpe@ona.fi.umag.cl

Ramón Blasco-Gimenez
Department of System Engineering and Automation
Technical University of Valencia
Camino de Vera, s/n. Valencia
Spain
rblasco@isa.upv.es.

Roberto Cardenas
Department of Electrical Engineering

University of Magallanes
Casilla 113-D. Punta Arenas
Chile
rcd@ona.fi.umag.cl

***Abstract*: The DC link voltage control of a PWM rectifier using a fuzzy logic based interpolation strategy for linear PI controllers is presented. The square of the DC link voltage is defined as the controlled variable to cancel the DC link voltage non-linear dynamics. The output of the fuzzy based controller depends on the DC link voltage error. For big DC link voltage error a controller with high closed loop natural frequency is used. As the DC link error reduces the bandwidth of the controller is reduced. Simulations and experimental results obtained with a 5kW experimental system are presented.**

I. INTRODUCTION

The advantages of the PWM rectifier for interfacing DC system into a grid or for AC/DC power conversion are well known: Low distortion supply current and close–to-unity power factor operation. These advantages make the PWM rectifier an attractive alternative for cage and doubly fed induction machines operating at variable speed in grid connected wind energy systems [1-3]. Several control strategies have been presented regarding the control of the currents and DC link voltage [4-8], including fuzzy logic and feedback linearization. The currents are controlled using vector control techniques in a synchronous rotating frame oriented along the supply voltage vector. For the control for the DC link voltage, the simplest control method uses a PI controller to process the error in the DC link voltage and set the active power component reference current. Because of time varying characteristic of the load a single PI controller will not assure a good dynamic performance over the entire operating conditions. In this paper, because of the time varying load characteristic of the rectifier, a fuzzy logic controller is used yielding to a robust control of the DC link voltage. The output of the fuzzy based controller will depend on the DC link voltage error. If the DC link voltage error is big then an equivalent PI controller with high closed loop natural frequency will be used. As the DC link error decreases an equivalent PI controller with a lower closed loop natural frequency will be selected. A linear fuzzy based interpolation between PI controllers is used. Given the non-linear nature of the DC link voltage dynamic, the square of the DC link voltage is defined as the controlled variable. High dynamic performance and low DC link voltage noise and ac currents are achieved. The control strategy has been simulated and experimentally verified.

II. CONVERTER MODEL.

Fig. 1 shows the converter schematic. L and R are the line filter inductance and resistance respectively and R_L represents an equivalent the load, which may be time varying and also be negative when power is injected into the supply.

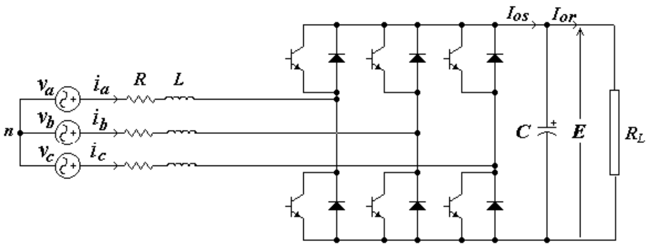

Fig. 1. Three-phase boost type PWM rectifier.

By balancing the power in the converter the following equations can be written to describe the dynamics of the DC link voltage, neglecting the losses in the converter.

$$\begin{aligned} &P_{ac} = k(v_{d1}i_d + v_{q1}i_q) = k(v_d i_d - Ri_d^2 - 0.5Lpi_d^2) \\ &0.5CpE^2 + GE^2 = P_{ac} \qquad\qquad G = 1/R_L \end{aligned} \tag{1}$$

Where v_d,v_q,,v_{d1},v_{q1}, i_d and i_q, are the supply and converter fundamental voltages and ac currents respectively in a synchronous frame, and k is a constant. C is the DC link filter capacitance. Neglecting the input filter resistance and inductance the dynamic of the DC link voltage will be given by:

$$\begin{aligned} &0.5CpE^2 + GE^2 = P_{ac} \\ &P_{ac} = kv_d i_d \end{aligned} \tag{2}$$

III. CONVERTER CONTROL STRATEGY.

Because of the time-varying and non-linear nature of the DC link voltage dynamics, the control scheme regulates the square value of the DC link voltage to cancel non-linearity in the DC link voltage. A classical PI controller may be used to regulate E^2 with P_d(=$kv_d\, i_d$) the demanded power as the output of the controller. Hence the following transfer function is obtained:

$$\frac{E^2(s)}{P_d(s)} = \frac{1}{0.5Cs + G} \tag{3}$$

In order to have a good dynamic performance and regulation (fast disturbance rejection) a PI controller should be designed with the highest natural frequency. However, the DC link voltage noise will limit the speed of the DC link voltage control loop. In order to achieve high dynamics performance and good regulation a fuzzy logic based interpolation of DC link voltage PI controllers is used. Different PI controllers are selected according to the error on the DC link voltage.

A. Linear PI Controller Implementation Using Sugeno Type Fuzzy Logic Structure

A digital linear PI controller is described by the following expression:

$$\begin{aligned} \frac{u(z)}{e(z)} &= K_p \frac{z-a}{z-1} \\ \Delta u_{PI} &= K_p e(k) - K_p a e(k-1) \end{aligned} \tag{4}$$

This linear PI controller can be implemented using a Sugeno type structure [9], with the membership functions for $e(k)=E^2{}_{ref}(k) - E^2(k)$ and $e(k-1)= E^2{}_{ref}(k-1) - E^2(k-1)$, shown in Fig. 2

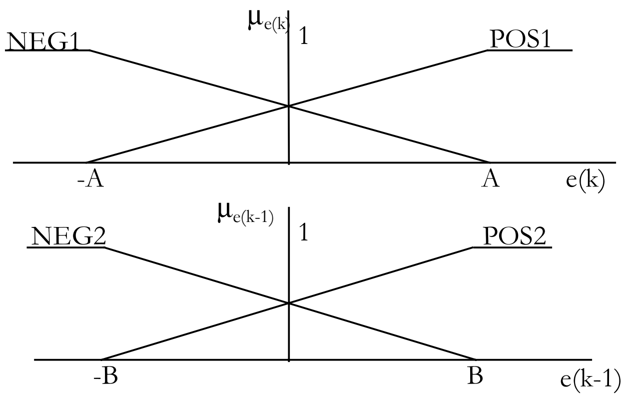

Fig. 2. Membership functions for an equivalent linear PI controller

And the following control rules.

IF e(k) *is* **POS1** *THEN output*=**C1**
IF e(k) *is* **NEG1** *THEN output*=**C2**
IF e(k-1) *is* **POS2** *THEN output*=**D1**
IF e(k-1) *is* **NEG2** *THEN output*=**D2**

Where *C1, C2, D1* and *D2* are function of the linear PI proportional and integral gains. *A* and *B* are user defined constants. If *C1,C2,D1* and *D2* are chosen such as:

$$\begin{aligned} C1 &= 2Ak_p \qquad & C2 &= -2Ak_p \\ D1 &= -2Bk_p a \qquad & D2 &= 2Bk_p a \end{aligned} \tag{5}$$

Then this Sugeno type structure is equivalent to the linear PI controller defined by (4)

*B. Fuzzy Based Interpolation of PI Controllers***.**

The control signal $|e(k)| = |E_{ref}(k) - E(k-1)| / k_e$, with k_e a scaling factor, is used for the linear interpolation between the PI controllers. In this work three PI controllers are considered with three membership functions for the control signal $|e(k)|$, S(Small), M(Medium) and B(Big), corresponding to small, medium and big DC link voltage error.

The input membership functions are shown in Fig. 3 and the rule base is shown in Table 1 (k_{pi} and a_i are the proportional gain and zero of the i-th PI controller (i=1,2,3)). The high method is used in the defuzzification process. A and B has been set to unity and e(k) and e(k-1) has been scaled such as the input domain remains between ±1

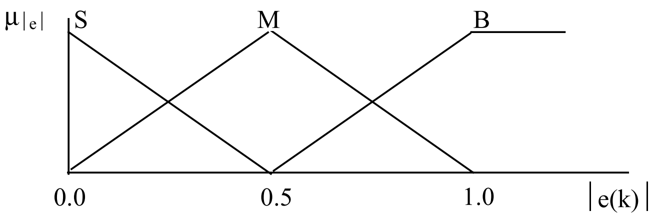

Fig. 3. Membership functions for the control signal

TABLE 1. RULE BASE FOR THE INTERPOLATION OF THREE PI CONTROLLERS.

e_k \ $\lvert e_k \rvert$	S	M	B
POS	$2k_{p1}$	$2k_{p2}$	$2k_{p3}$
NEG	$-2k_{p1}$	$-2k_{p2}$	$-2k_{p3}$

e_k \ $\lvert e_k \rvert$	S	M	B
POS	$2k_{p1}$	$2k_{p2}$	$2k_{p3}$
NEG	$-2k_{p1}$	$-2k_{p2}$	$-2k_{p3}$

Each PI controller has been designed using standard control tools using the plant defined by (3). The output of the fuzzy controller is the change in demanded power $\Delta P_{d,ref}$. The demanded power $P_{d,ref}$ and the demanded active power current component $i_{d,ref}$ are given by:

$$\begin{aligned} P_{d,ref}(k) &= P_{d,ref}(k-1) + \Delta P_{d,ref}(k) \\ i_{d,ref}(k) &= \frac{P_{d,ref}(k)}{kv_d} \end{aligned} \tag{6}$$

For variable speed wind energy applications, because of random characteristic of the wind resource the generating conditions are generally unknown, hence the generated power (in this case $P_G=EI_{or}$) can be considered as a disturbance for the DC link control loop. Hence the DC link voltage plant in (3) is reduced to a pure integrator and again classical control theory can be used to design the PI controllers.

The transition between different PI controller using the proposed fuzzy based interpolation is smoothly. The output of the fuzzy controller when interpolating between two PI controllers corresponding to closed natural frequencies of ω_{01} and ω_{02} is given by:

$$PI_{fuzzy} = \alpha PI_{\omega 01} + (1-\alpha) PI_{\omega 02} \tag{7}$$

Where α is a gain ($0 < \alpha < 1$), which depends on the value of the control signal. Using (7) and the system plant the equivalent closed loop natural frequency and damping factor of the control system can be obtained.

Fig. 4 shows the resulting closed loop natural frequency of the DC link voltage control system during the transition between two PI controllers as a function of the control signal. The PI controllers have been designed to have a control system with closed loop natural frequencies equal to 13rads^{-1} and 25rads^{-1} respectively with the same damping factor. A similar result is obtained for the system closed loop natural frequency when the PI controllers have different damping factor

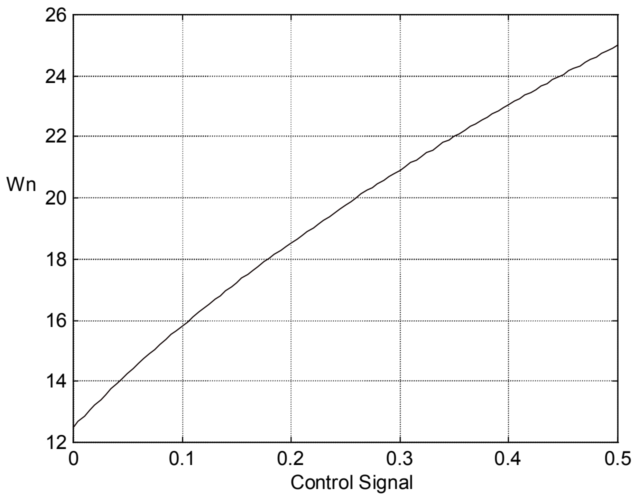

Fig. 4. Controller closed loop natural frequency during the transition of two PI controllers

Fig. 5 shows the equivalent damping factor ξ of the fuzzy logic controller during the interpolation of the two PI controllers mentioned above as function of the control signal. As can be seen during the interpolation the damping factor reduces slightly and a small increase in the overshoot may be expected.

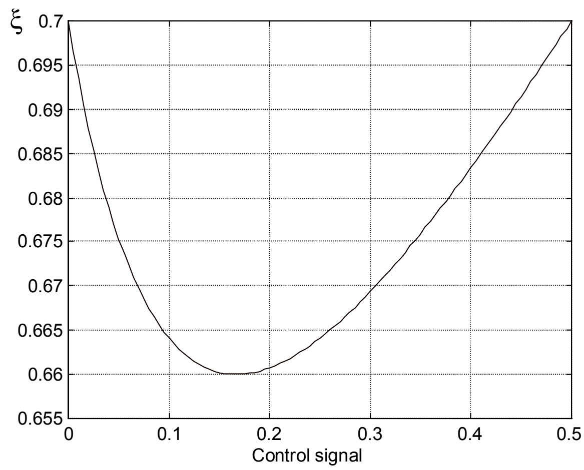

Fig. 5. Controller damping factor during the transition of two PI controllers

Fig. 6 shows the equivalent fuzzy controller damping factor ξ during the transition between two PI controller with different damping factor. It shows a smooth transition between the two damping factors.

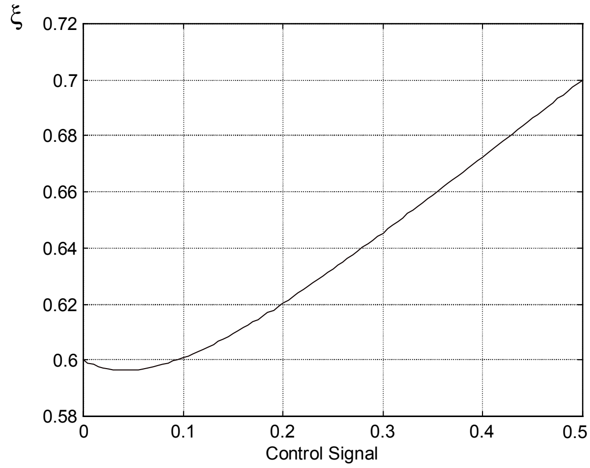

Fig. 6. Controller damping factor during the transition of two PI controllers with different damping factor.

IV. Simulation And Experimental Results.

A Simulation Results.

The system has been simulated using Matlab. The simulation includes the vector control of the AC input currents, the converter model and a 1kHz PWM strategy. The rated power of the converter is 5kW, with L=12mH, R=0.1Ω and C=1200μF. Three fuzzy equivalent PI controllers have been implemented corresponding to three closed loop natural frequencies: ω_{01}=10rad/s, ω_{02}=70rad/s and ω_{03}=140rad/s, respectively. Fig. 7 shows the response to a step change in DC link voltage reference from 600V to 720V at t=0.1s. The top graphic in Fig. 7 shows the step response performance for each PI controller. The bottom graphic in Fig. 7 shows the performance of the fuzzy based interpolation strategy for this condition. The time response for the equivalent fuzzy controller is equivalent to the single PI controller with the highest natural frequency.

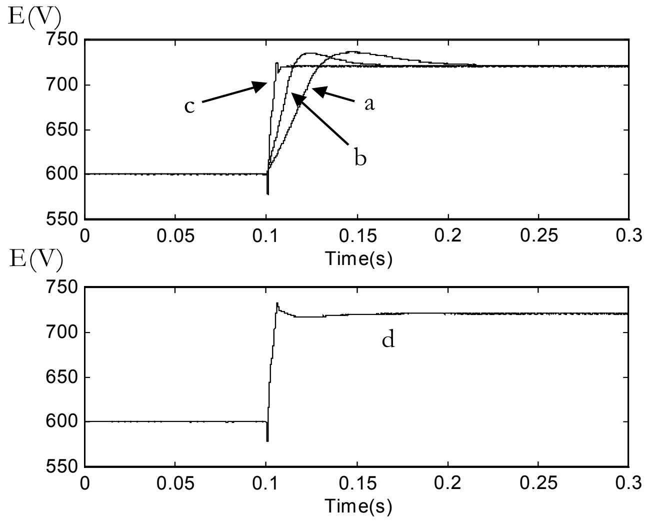

Fig. 7. DC link voltage Step response. a) ω_{01}=10rad/s, b) ω_{02}=70rad/s, c) ω_{03}=140rad/s and d) Proposed controller.

Fig. 8 shows the control performance to a 5kW-load step disturbance. The top graphic shows the performance of each PI controller. As expected good, regulation of the DC link voltage is obtained with the PI controller corresponding to the highest closed loop natural frequency but with a noisier signal.

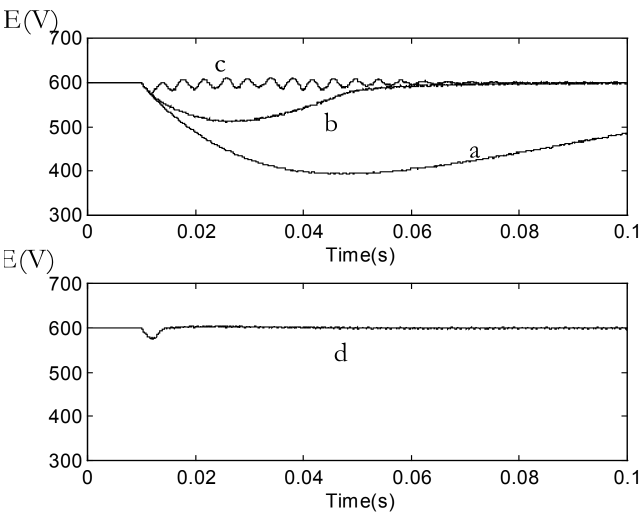

Fig. 8. Controller performance for disturbance rejection.. a) ω_{01}=10rad/s, b) ω_{02}=70rad/s, c) ω_{03}=140rad/s and d) Proposed fuzzy controller

B. Experimental Results for the DC Link Voltage Regulation.

The disturbance rejection performance of the DC link voltage controller has been tested on a 5kW experimental rig, shown in Fig. 9. The DC link voltage is regulated at 550V and the supply voltage has been adjusted to 250V via a three-phase variac, providing enough modulation index excursion during transients to avoid overmodulation problems. Step load changes have been applied using a chopper controlled resistive load connected to the DC link. Three DC link voltage PI controllers have been implemented with closed loop natural frequencies of ω_1=20rads^{-1},ω_2=60rads^{-1} and ω_3=120rad^{-1} respectively.

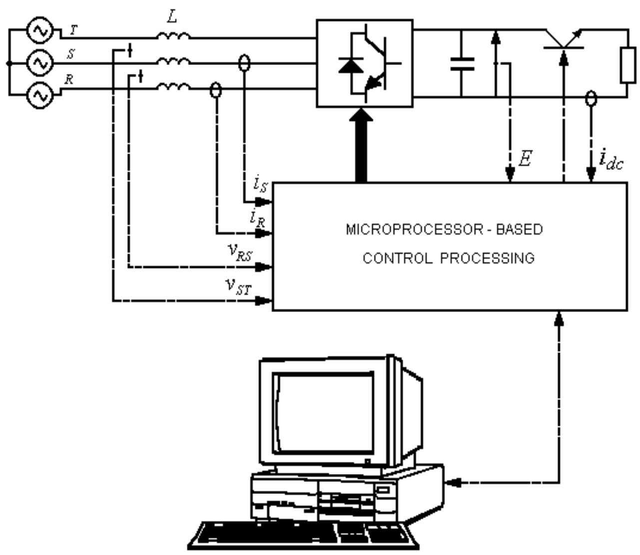

Fig. 9. Experimental set-up.

A microprocessor network controls the entire system, including the vector control of the supply converter currents, the DC link voltage control loop and the calculation of the timings of a 1kHz asymmetric regular sampling PWM. The sampling of the currents and voltages as well as the control loops is set to 0.5ms.

The performance of the controller to a step change in reference voltage is shown in Fig. 10. The reference voltage is changed from 550(V) to 550(V) at t=0.25s. The response of the fastest and lowest PI controller as well as the fuzzy based controller is shown. As seen in Fig. 10 the response of the proposed fuzzy controller is similar to the fastest PI controller.

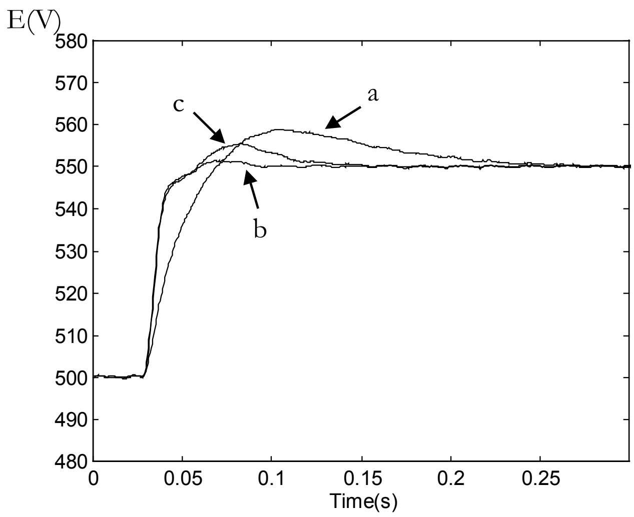

Fig. 10. Controller performance to step change in reference voltage. a) ω_{01}=20rad/s, b) ω_{02}=120rad/s and c) Proposed fuzzy controller

The performance of the controller to load disturbance rejection has been studied applying a 2.0kW load impact to the DC link. The load is connected at t=0.1s and disconnected at t=0.9s. Fig. 11 shows the disturbance rejection performance of the slowest PI controller. The top graphic in Fig. 11 shows the DC link voltage and the bottom graphic shows the d-axis reference current. The noise in the d-axis reference current is quite small however the voltage excursion is above 50V.

Fig. 12 shows the DC link voltage performance for the same load impact with the faster PI controller. Again the top graphic is the DC link voltage and the bottom graphic is the reference active power current. The disturbance rejection is very good with a maximum excursion of the DC link voltage of about 20V, however the noise in the d-axis current is noticeable

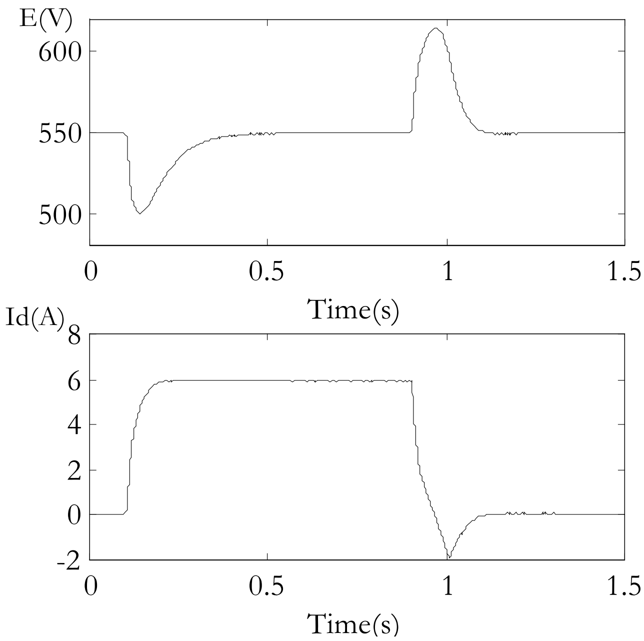

Fig. 11. DC link voltage performance with a slow PI controller

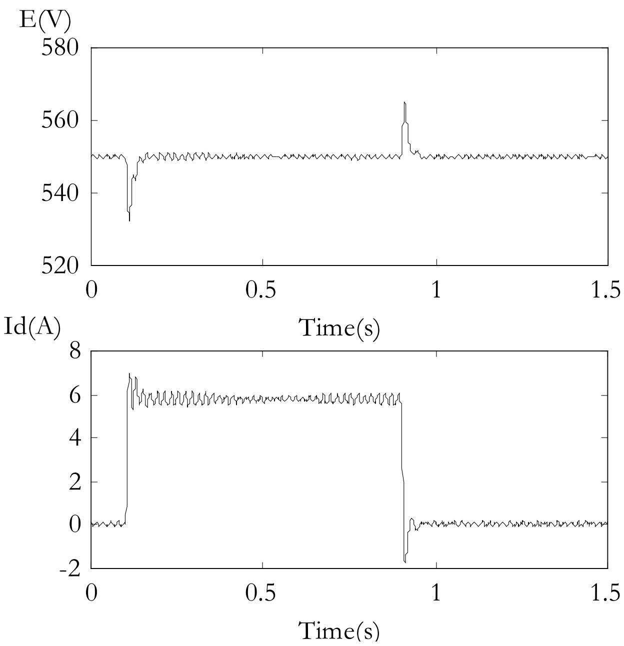

Fig. 12 DC link voltage disturbance rejection with a fast controller.

Fig. 13 shows the performance of the proposed fuzzy based DC link voltage controller with a linear interpolation of PI controllers, for the same load impacts. As seen from Fig. 13 the voltage regulation is also good, with a maximum excursion of 22V, but the steady state noise in the d-axis reference current is kept very low.

In the proposed strategy the controller has low closed loop bandwidth for small DC link voltage errors, in order to keep reduced noise, and high closed loop bandwidth for high DC link voltage errors hence excellent load impact rejection is maintained.

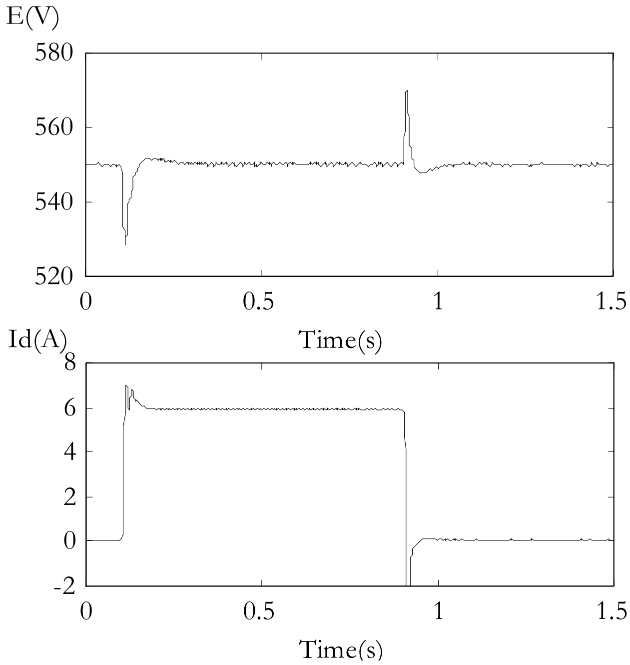

Fig. 13. DC link voltage performance with the proposed fuzzy controller

V. FINAL REMARKS

A fuzzy logic based controller for DC link voltage regulation of a three-phase PWM boost type rectifier has been presented. The strategy is based on linear interpolation of different linear PI controllers. Different closed loop natural frequency controllers are used depending on the DC link voltage error. Therefore high dynamic performance is achieved for disturbance rejection while keeping steady state DC link voltage and ac current noise to a minimum. The strategy has been simulated and experimentally verified.

VI ACKNOWLEDGEMENTS

The financial support provided by Fondecyt, through projects 1980688 and 7980077, is kindly acknowledged. The financial support from the Conselleria de Educacion y Cultura de la Generalitat Valenciana, through project ref INVO1-36, is kindly acknowledged.

VII REFERENCES.

[1] Jones S.R., Jones R., "A Control Strategy for Sinousoidal Supply Side Convertors", IEE Colloquium on Developments in Real Time Control for Induction Motor Drives", DIGEST No. 1993/024, 1993.

[2] Peña R.S., Crdenas R., Blasco-Gimenez R.,Asher G.M., Clare JC. A cage induction generator using back to back PWM converters for variable speed grid connected wind energy system. IECON2001. Denver USA, 2001

[3] Peña R.S., Clare JC, Asher GM, "A doubly fed induction generator using back to back PWM converters and its application to variable speed wind energy generation", IEE-Proceeding part B (Electric Power and Applications), pp. 231-241,1996.

[4] Rim C T., *et al,* "A complete DC and AC Analysis of Three-phase Current PWM Rectifier Using d-q Transformation", IEEE Trans. on Power Electronics, Vol. 9, No. 4, 1994, pp. 390-396.

[5] Zargary N, Joos G, "Performance Investigation of a Current-controlled Voltage-regulated PWM Rectifier in Rotating and Stationary Frames", IEEE Trans. on Ind. Electronics, Vol. 42, No. 4, 1995, pp. 396-401.

[6] Rodríguez J., *et al.* "Control of a three phase PWM front-end rectifier using fuzzy logic". EPE'97. Vol. 2 pp. 438-443. Norway. 1997.

[7] Stergiopoulus F *et al.* "A new fuzzy logic control scheme for three phase AC/DC PWM converters implemented in a DSP." . EPE'99. Lausanne. Switzerland. 1999.

[8] Jung J., *et al*, "A feedback linearizing control scheme for PWM converter-inverter having a very small DC-link capacitor". IEEE Trans. On Ind. Application, Vol 35, No 5, pp.1124-1131.

[9] Hakan A., Asher G., Clare J., "Equivalence of fuzzy and classical controller: An approach to fuzzy control design". EPE'99, Lausanne. Switzerland. 1999.