Application of the 3-Phase Power Factor Correction Rectifier in DC Drive

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Abstract – **This paper presents investigation in application of the power factor correction (PFC) rectifier prototype in DC drive system. The device features are current hysteresis control strategy, operation with unity power factor and sinusoidal input current, and maintaining a constant DC voltage. Regeneration capability and some fault mode operation are also possible. After establishing simulation model and based on achieved simulated results we realized prototype and used it as an input power unit in DC drive. Experimental results are reported and they confirm applicability to rectifiers in drive systems.**

Keywords – **PFC rectifier, DC drive, power factor, SPICE**

I. INTRODUCTION

The latest international and national standards (IEC 61000-X, IEEE 519-1992, JUS N.A6.101-103) define considerable rigorous conditions for harmonic distortion and the minimum power factor value ([1]). The realization of the standards, mentioned above, has been the research subject of the scientists in the field. Application of novel power electronics components makes possible different topologies of power converters and applications of new control techniques ([2]). Usage of digital controllers (microcontollers and DSP) allows implementation the newest control methods: sliding mode control, variable structure system control, predictive control, utility voltage orientation, etc. The hysteresis control technique, which is known as an effective method of control of non-linear systems, also offers some significant advantages as the robustness, low noise operation and simplification.

Having in mind that electrical drives present one of the main electrical power consumer (about 50%) in wide range of power, significant part of the PFC rectifiers research follows that mentioned above field. Most of converters, applied in electrical drives, have a power rectifier as an input unit. The most of actual applicable rectifiers are three-phase diode bridges ones. In some applications, (crane, re-winder drives, some multi-motor drives) the possibility of bi-directional power flow is significantly economical. In these applications, the regenerated power becomes more effective to dissipate in braking resistor. Firstly, it's necessary to compare all aspects of concrete application of PFC rectifier: price, reliability, simplicity and input current and voltage quality. Input unit in modern drive is going to be PFC rectifier, but motor supplying, according to the kind will be done by chopper or inverter.

This paper presents the PFC rectifier projecting method procedure based on computer simulations. Invented rectifier was simulated and tested in details in different operation modes: utility voltage asymmetry and its increase, overloading, transient and power-reversal tests. In addition, the operation of the separately excited DC motor with current regulated chopper was simulated and investigated. Finally, the complete DC drive with PFC rectifier was simulated and experimentally tested. All of the theoretical and simulation results are experimentally verified.

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II. THREE PHASE POWER FACTOR CORRECTION RECTIFIER

Fig. 1 shows the schematic of the voltage sourced current controlled PFC rectifier The main circuit consists of a bridge rectifier mode up of six power transistors (MOSFET IRF840) with anti-parallel diodes which is connected to the three-phase supply through an boost filter inductor *L*. High voltage electrolytic capacitor $C = 2.2mF$ is placed on the DC side of the converter. The load current is shown as time dependent variable $i_{DC}(t)$.

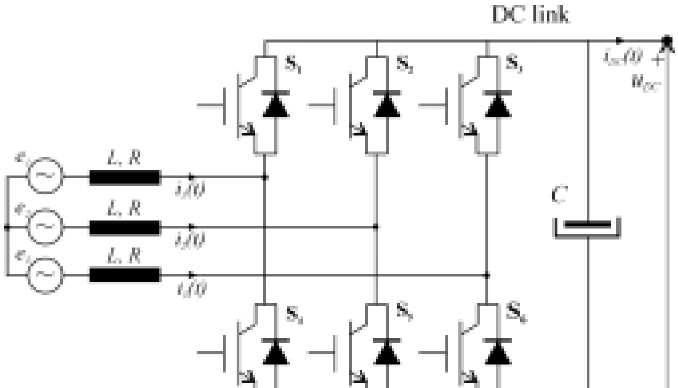

Fig. 1. Circuit diagram of a three-phase PFC rectifier

PFC rectifier control circuit is composed by using an analogue and digital technique. Inner control loop was accomplished by using analogue hysteresis current controller (also known as delta modulator). Outer control loop is realized digitally using embedded PC ISA card on which DC voltage PI control algorithm was developed. Except control, mentioned PC card has to synchronize generated reference currents with utility voltage. Through gate driver circuit IR 2110 switching signals are taken to MOSFET gates (Fig. 2).

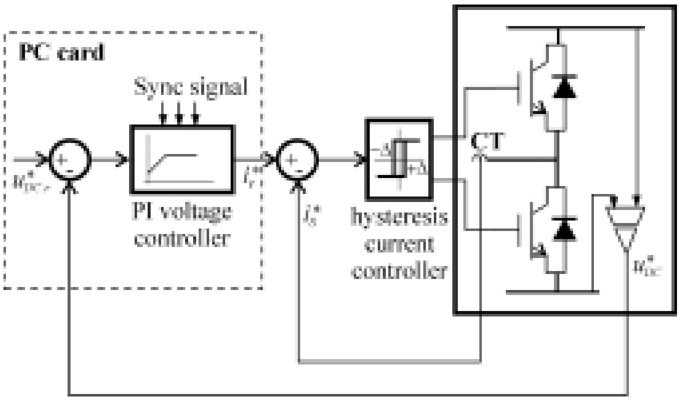

Fig. 2. Control circuit of a three-phase PFC rectifier

The output voltage signal u_{DC}^{*} is compared with reference voltage u_{DCr}^{*}. The error signal feeding PI voltage controller and is than passed through a limiter to obtain amplitude of the phase current reference signals (I_{r1}^{*}, I_{r2}^{*}), while the third phase reference current amplitude is obtained by:

$$I_{r3}^{*} = -(I_{r1}^{*} + I_{r2}^{*}) \quad (1)$$

Synchronizing signals triggered ROM stored waveforms corresponding reference current amplitude. Non-inverted pin in delta modulators is supplied by the triggered waveforms through 8-bit D/A converters. Inverted pin is powered by voltage signals i_{s1}^{*} and i_{s2}^{*}, which correspond to instantaneous input current values, obtained from Hall wideband current transducers (CT). Similarly, to Eq. (1), the third input current signal is received by:

$$i_{s3}^{*} = -(i_{s1}^{*} + i_{s2}^{*}) \quad (2)$$

It's necessary to stress the fact that using only two Hall current transducers a significant effect is also obtained beside the money saving. This fact is that the receiving i_{s3} signal according to the Eq. (2) leads to the input currents balance in all dynamic and stationary states (in case CT offset presence or phase interruption). Signals, obtained in according to Eqs. (1) and (2) result power balance between output and input sides of the converter, which is essentially important for system stability.

We have to note that momentary value DC link voltage always has to be greater than $\sqrt{6}E$ (E is RMS value of input voltage) which represents current distortion limit ([3]). If it is commanded DC bus voltage value lower then the mentioned limit, the bridge diodes will charge the bus capacitor and input currents will be distorted.

III. DC MOTOR DRIVE

For experimental investigation, we realized a two quadrant DC motor drive with current controlled DC-DC chopper. Cascade control scheme ([4]) consists of inner hysteresis current control loop and outer speed PI control loop; the both of them realized in analog technique. Current limit is achieved by limiting the current reference produced by the superimposed speed controller.

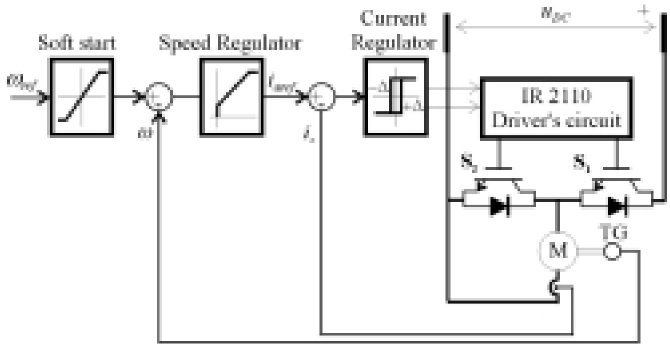

Fig. 3. DC motor drive with current controlled chopper

As switching transistors it was used MOSFETs IRF840 with incorporated anti-parallel diode and RCD snubber's circuit. For experimental purpose as DC motor load, it was used speed controlled AC motor, which was in hard mechanical connection. Increasing the speed over no-load speed DC motor acts as a generator, i.e. it runs in braking mode.

IV. MODELING AND SIMULATION

The methods of the research in PFC rectifier, using computer is the following ones: firstly, the mathematical model was established, and then based on posed aims the simulation program was applied. After the prototype building, more accurate computer models were used for final device design. For the practical converter design the most important thing was SPICE simulation, but MATLAB simulation was helping step in parameter controller fitting. Based on MATLAB macro model of the system we discussed system stability and response in variable load cases as DC motor ([3]).

For a circuit shown in Fig. 1 generalized mathematical model ([5], [3], [6]) it can be established in state space form. According to the analysis itself the following models are appropriate: steady state model, low frequency model, high frequency model or small signal ac model. Accurate library and user created models of the system components (Figs. 1. and 2) were used in SPICE simulation of the PFC rectifier. Before all it was simulated PFC rectifier operation under variable resistive load (from no-load to full load). The achieved results acted as a leading criterion for power semiconductor choice (Fig. 4) and adjusting of the protecting function in driver circuit especially in asymmetric mode operation (Fig. 5).

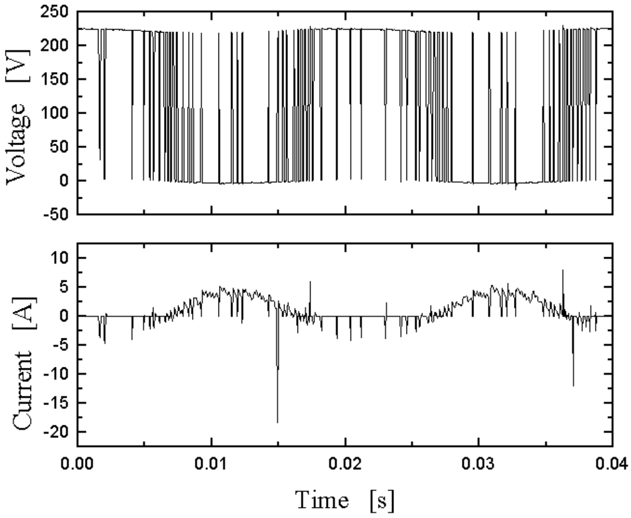

Fig. 4. MOSFET drain - source voltage and current

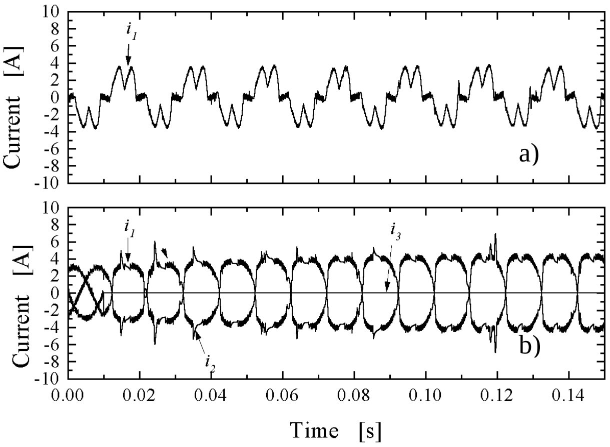

Fig. 5. Main supply currents: a) DC link voltage below current distortion limit ($u_{DC} < \sqrt{6}E$), b) phase 3 break

From the point of view of voltage control loop, internal current control loop presents subsystem whose dynamics needn't be taken into consideration (equivalent transfer function has a gain). So, system dynamic can be analyzed a bit simply by using system macro model based on equation of instantaneous power balance:

$$\sum_{i=1}^{3} p_{si} = \sum_{i=1}^{3}\left(R_{tot}\, i_i^2 + L\, i_i \frac{di_i}{dt}\right) + u_{DC}\, C \frac{du_{DC}}{dt} + p_{load} \tag{3}$$

where is: p_{si} - main supply instantaneous phase power ($\sum_{i=a}^{c} p_{si} = \sum_{i=1}^{3} e_i\, i_i$); p_{load} - load power (in case of resistive load $p_{load} = \frac{u_{DC}^2(t)}{R_{load}}$) and $R_{tot} = R + R_S$ (R is boost inductor resistance, R_S is switch on-state resistance). The other signs are shown in Fig. 1. Having in mind that AC voltage and current are clearly sinusoidal, neglected DC voltage and current ripple, and assuming 100% converter efficiency power balance equation relating the AC power to the DC power can be written as:

$$\sqrt{3}E\, I \cos\phi = 3R_{tot} I^2 + 3LI \frac{dI}{dt} + U_{DC} \cdot C \frac{dU_{DC}}{dt} + \frac{U_{DC}^2}{R_{load}} \tag{4}$$

where is E and I RMS values of input voltage and current, respectively, ϕ is phase angle between input voltage and current, and U_{DC} is mean value of DC link voltage. Beside this equation, considering that the reference current signal ideally follows input current signal, it can be written the following one:

$$I = G_r(s) U_{DC} \frac{1}{\sqrt{2}} \tag{5}$$

where is $G_r(s)$ DC voltage feedback loop transfer function, which includes voltage sensor attenuation, and low-pass filter transfer function (with cut-off frequency $f_{BW} = 300Hz$).

After the lineariziation Eq. (4) had been done the transfer function was achieved:

$$W_o(s) = \frac{\Delta U_{DC}(s)}{\Delta I(s)} = \frac{\sqrt{3}E\cos\phi - 6RI_0 - 3LI_0\, s}{CU_{DC0}\, s + 2\frac{U_{DC0}}{R_{load}}} \tag{6}$$

where subscript '0' denotes steady state operational point.

Voltage control block diagram is shown in Fig. 6. In this figure block $W_{SH}(s)$ represents PC card A/D converter sample & hold time and voltage to integer discrete value conversion ratio.

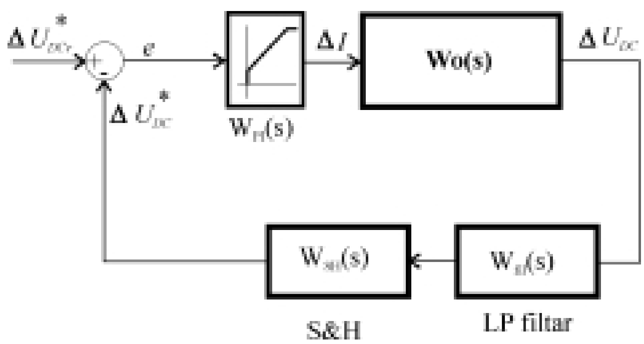

Fig 6. DC link voltage control loop

The parameters of PI controller are fitted on the basis of technical requirements (rise time and overshoot value) in the first step, and then because of the system non-linearity, the fine tuning is made more precisely by using the experiment of Takahashi's procedure.

V. Experimental results

The main feature of the investigated rectifier can be seen in Fig. 7 below presented.

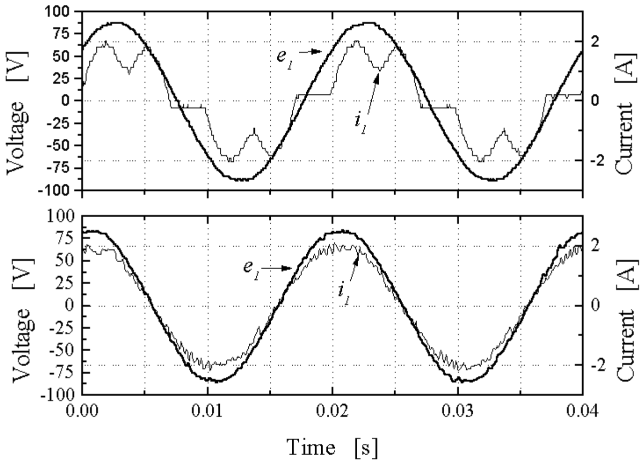

Fig 7. Input voltage and current: three-phase diode rectifier (top); PFC rectifier (bottom)

Considerable improving of input current shape can be seen at the first sight which also can be verified by comparative calculation of current total harmonic distortion (*THDI*) and input power factor (*PF*) in Table 1.

TABLE 1
COMPARISON OF TWO DIFFERENT RECTIFIER TYPES

Rectifier types	***THDI***	***PF***
3 phase diode bridge	32 %	0,95
3 phase PFC	7,71 %	0,996

We experimentally tested device function during the DC drive acceleration and deceleration and some results are shown in Fig. 8.

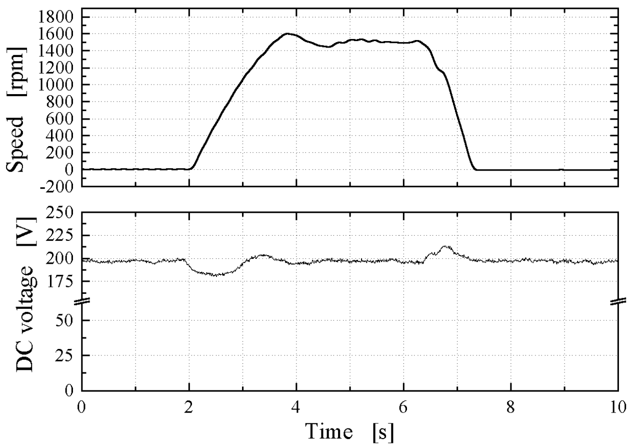

Fig. 8. DC drive acceleration and deceleration: speed (top), DC link voltage (bottom)

Finally, we tested possibility of regenerative power flow and input current/voltage is presented in Fig.9.

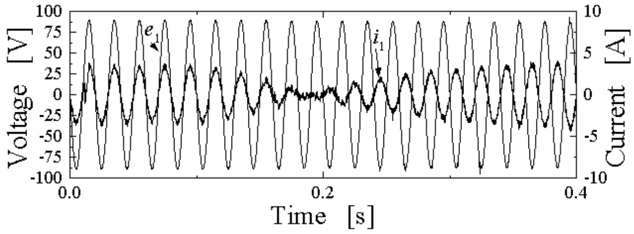

Fig 9. Input voltage and current during the change from rectifier to regenerative mode operation

VI. Conclusion

The mathematical and adequate SPICE models have been used as an efficient design tool. For voltage controller synthesis, we used a simple model, based on power balance equation. Various numbers of transient tests under normal and abnormal operating conditions approved expected PFC rectifier performance.

The realized PFC rectifier with the current-forced control makes a good voltage regulation, sinusoidal line current and nearly unity power factor possible. Clearly, the PFC rectifier more complex and more expensive than conventional 3-phase bridge rectifier. The device is suitable as a power source in variable speed drive systems with bi-directional power-flow capability

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