Verification of Control Behaviour of Three-Phase Voltage-Source Active Rectifier with Vector Control

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Abstract **– This paper is focused on creating a model of vector control of voltage-source active rectifier in MATLAB® software. That model was afterwards implemented to TMS320F28335 microcontroller unit which was used for control of laboratory converter. Results obtained from the simulation and from measurements on the low-power laboratory stand.**

Keywords- Voltage-source active rectifier; Vector control; Active filter; Converter for power symmetrization; MATLAB®; Simulink®; PLECS®

I. Introduction

The paper is composed from two main parts. The first one is creating of mathematical model of three-phase voltage active rectifier (include of dead time and losses of semiconductors components, where their influence is described in [1], [2]). Nowadays are voltage source-active rectifier used more and more because of their advantages such as increasing of DC voltage in DC-link, recuperation possibility, generated harmonic currents [3] or ability of control power factor [4]. The second part is design of control which is inspired by principle of Vector control used for controlling of electrical drives. Advantage of the design of regulation is availability to demanding of separate control of active and reactive on requirement value. Control also ensure that current which is drawn from the grid is without reactive power or with required value. For example if we want to compensate reactive power of the grid. Interesting papers deals with vector control of voltage-source active rectifier for a specific application are [5], [6] and [7].

II. Model of Converter for Power Symmetrization

The simulation model and interface for testing control algorithm was created in MATLAB®/Simulink®/PLECS® software. The whole system is solved discretely with 10 kHz sampling period, derived from modulation frequency of pulse width modulation (PWM).

Created simulation model is divided to two models. First one model is power part representing grid, load and converter. The second part is a controlling structure of converter. In real application the controlling is realized by microprocessor, therefore is used discrete form of control also for this model. The delay caused by signal processing by the microprocessor by one sample, derived from the sampling frequency, is taken into account.

The reason why we dealt with creating such accurate model because we then use rapid-prototyping for creating C-code applicable for our digital signal processor as described in III.

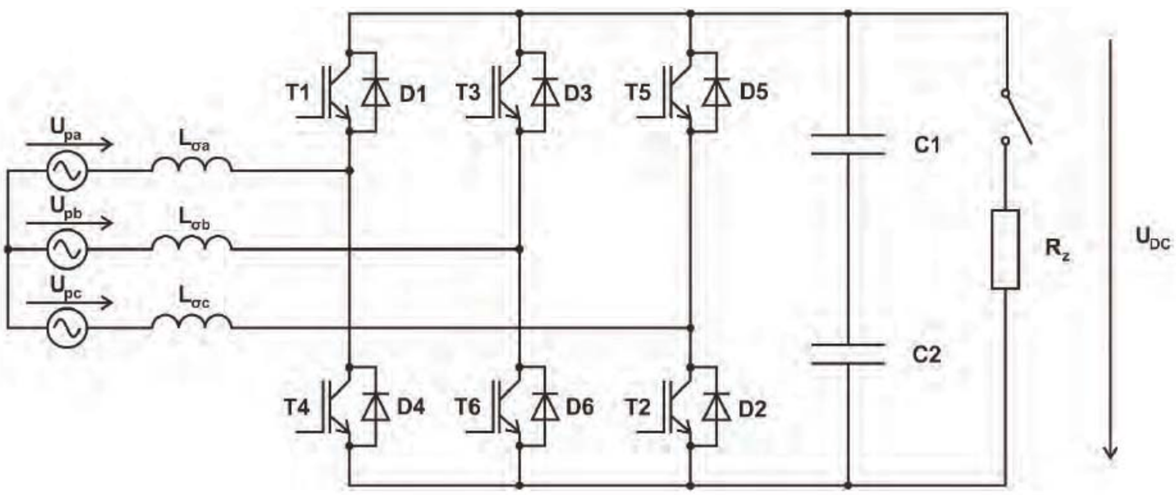

Fig. 1: Diagram of power part of voltage source rectifier

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Power part of mode is in the Fig. 1. Three power AC sources are shifted by 120° and representing power grid. Inductors $L_{\sigma a}$, $L_{\sigma b}$, $L_{\sigma c}$, represent reactance of the grid which is necessary for voltage-source active rectifier function. The converter itself is composed from six IGBT parts (T1 – T6) with anti-parallel diode (D1 – D6) represents model of the converter. Voltage DC-link is represented by two serial capacities.

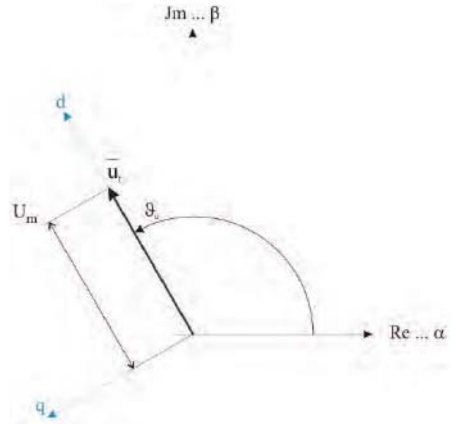

Fig. 2: Definition of rotating d,q reference frame

In the Fig. 3 is shown control structure used for voltage-source active rectifier, inspired by vector control of AC electrical drives. As first is necessary transform the three-phase voltage power grid frame a, b, c to static reference frame α, β, γ (1) to get ϑ angle (2) which makes the power grid synchronization and voltage U_m (3) usable for feedforward. After obtain of ϑ angle is possible to transform currents to rotation d, q, reference frame (3). Definition of rotating d, q reference frame shown in Fig. 2.

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_\gamma \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (1)$$

$$\vartheta = \tan^{-1}\left(\frac{u_\beta}{u_\alpha}\right) \quad (2)$$

$$U_m = \sqrt{{u_\alpha}^2 + {u_\beta}^2} \cdot \sqrt{\frac{2}{3}} \quad (3)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\vartheta) & \cos\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) \\ -\sin(\vartheta) & -\sin\left(\vartheta - \frac{2\pi}{3}\right) & -\sin\left(\vartheta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

Thus transformed real currents are brought to PI controller (R_{id} and R_{iq}), that can be used thanks to d,q transform and whose output is voltage demand in d,q reference frame. To PI controller R_{iq} which take care of active power part is superior another PI controller R_{UDC} which one holds demanding voltage in the DC-link. The influence of capacitor value and switching frequency on the DC-link voltage ripple is in [8]. For acceleration of control loop is used feed-forward equations (5) (6) in mathematical model box for gross value of demanding voltage generated by converter.

There is used symmetrical limiter for PI voltage controller (R_{UDC}), where the limits (I_{max} and I_{min}) are depends on nominal converter power. The limiters for voltage controllers are set according to PWM overmodulation. During saturation is stopped the integration of PI controllers. However, the final signals (u_{vd} and u_{vq}) are calculated by sums of feedforward and outputs of PI controller. That is the reason for using limiters before inverse transformation again (PWM overmodulation).

$$u_{d\_model} = U_m - R \cdot i_{d\_w} + \omega \cdot L \cdot i_{q\_w} \quad (5)$$

$$u_{q\_model} = -R \cdot i_{q\_w} - \omega \cdot L \cdot i_{d\_w} \quad (6)$$

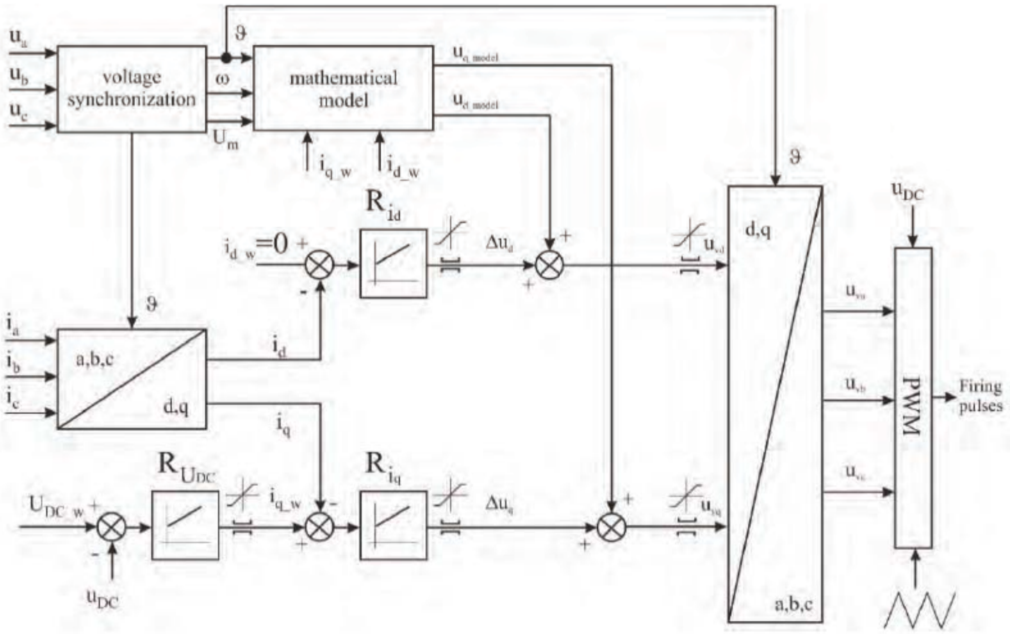

Fig. 3: General structure of vector control for voltage source inverter

Because of the output of PI current controllers R_{id}, R_{iq} and feed-forward are in d, q rotation reference frame it is necessary to transform them back to three phase. It is done by inverse transformation of equation (4) for voltage and by ϑ angle again. Signals of reverse transformed voltages are compared with modulation saw which is well known pulse width modulation (PWM) with scale to DC-link voltage.

III. Laboratory Measurement

After the tuning of the PI controllers was whole control structure implemented to microcontroller TMS320F28335 which is commonly used at our department for drive control. Implementation was done via MATLAB® again where were used rapid prototyping libraries that allows convert the created mathematical model to C-code intelligible for microcontroller.

Thanks to a limited range of A/D converters was measurement done on low voltage, but that was a little advantage for us in the end because are there intense of dead time (3µs), part parameters etc. As the grid was used regulated three-phase voltage supply and three-phase common core inductor as leakage inductance. Thanks to common core is cased current asymmetry, which is best visible without switching (Fig. 4), which was included to the simulation later.

Fig. 5 shows steady state where is shown constant DC-link voltage, held by PI controller R_{UDC}. Drawn phase current i_{pa} is without lagged behind the phase voltage of the grid as requested. Harmonics of this current is more acceptable from harmonic distortion point of view in compare of current drawn from the grid by simple diode rectifier (Fig. 4).

In the Fig. 6 is captured response of controller R_{UDC} on step load connection and step disconnection with nominal value 90W.

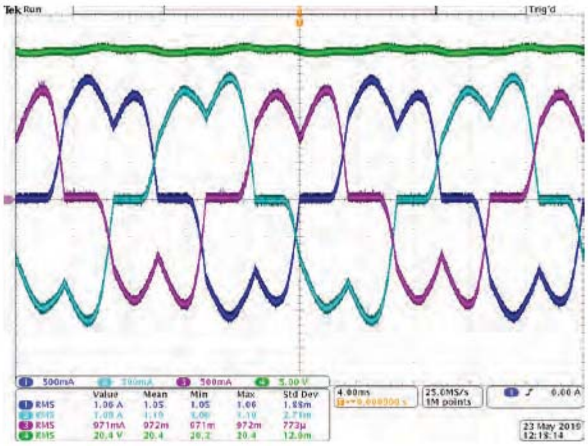

Fig. 4: Currents drawn from the grid without switching (simple diode rectifier) Ch1:phase current i_a; Ch2:phase current i_b; Ch3:phase current i_c; Ch4: DC-link voltage

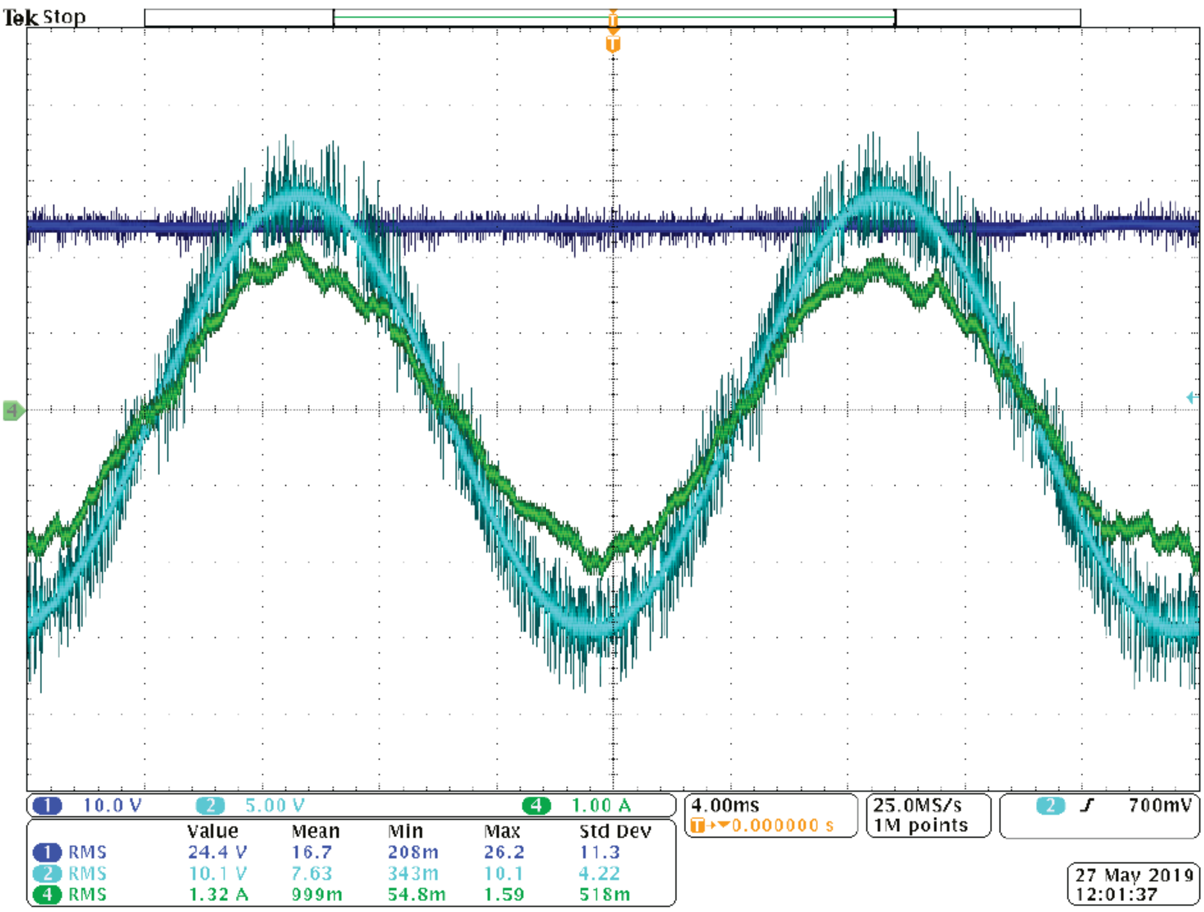

Fig. 5: Active rectifier voltages and phase current under steady-state Ch1. DC-link voltage; Ch2: Phase voltage u_{pa}; Ch4: Phase voltage i_{p1}

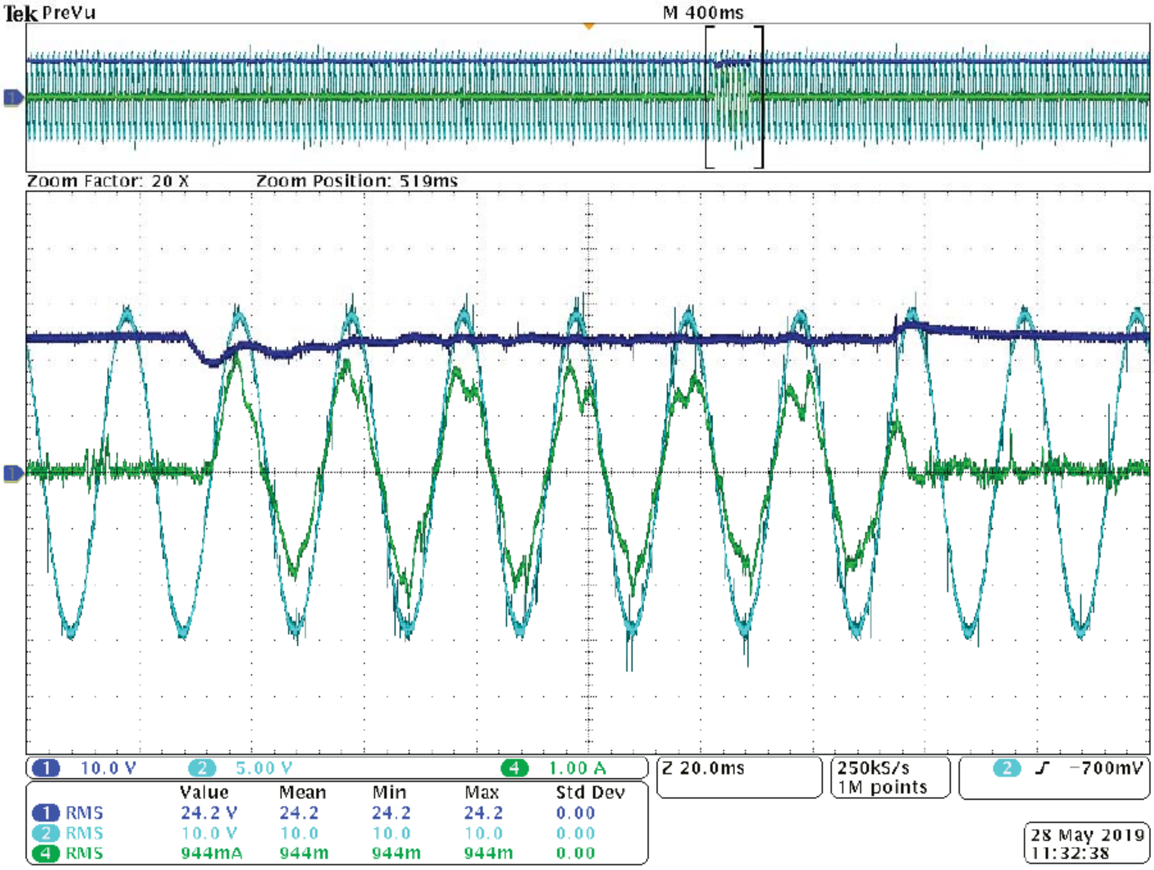

Fig. 6: DC-link voltage control with load change.
Ch1. DC-link voltage; Ch2: Phase voltage u_{pa}; Ch4: Phase voltage i_{pa}

IV. Conclusion

The paper describes vector control of three-phase voltage source active rectifier. The control was tested and tuned by simulation model in MATLAB® software.
After that was used the rapid-prototyping method for convert the simulation structure to C-code and fill into microcontroller. The advantage of this method is fast way how to verify functionality of designed and afterward simply reach variability for practical use. Vector control method is promising solution for voltage-source active rectifier connected to the grid thanks to ability to control power factor. That attribute makes it great in power symmetrization field or for active filter. Further extension will be used for power symmetrization of traction power station.

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