Application of Active Front End Rectifier in Electrical Drives

Bojan Banković[1], Nebojša Mitrović[2], Vojkan Kostić[3] and Milutin Petronijević[4]

Abstract – **The term Active Front End Inverter (AFE) refers to the power converter system consisting of the line-side converter with active switches such as IGBTs, the dc link capacitor bank, and the load-side inverter. The line-side converter normally functions as a rectifier. During regeneration it can also be operated as an inverter, feeding power back to the line. This paper presents some applications of active front end rectifiers in induction motor drives.**

Keywords – **Induction motor, Active front rectifier.**

I. INTRODUCTION

Modern electrical drives can consist of different electrical machines such are induction motors and different converter topologies with various control algorithms. Some of them had to have adjustable speed and should be capable of energy saving. It could be achieved with the usage of very efficient machines and converter components and with the recuperation capability of electrical power into the grid. AC/DC Voltage Source Converters (VSC) are widely used in industrial AC drives as Active Front End (AFE), DC-power supply, power quality improvement and harmonic compensation (active filter) equipments [1], [2], [3]. The use of the AFE meets the requirements for efficient energy feedback to the network.

There are several possibilities for realization of breaking or recuperation in the electrical drives. One of them is usage of the inverter with diode rectifier on line side, DC-link capacitor with brake resistor and brake chopper as it is shown on Fig. 1.

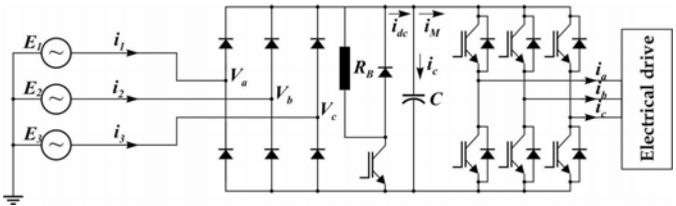

Fig.1. The AC-AC inverter with diode rectifier, DC-link capacitor, brake resistor, brake chopper and DC-AC drive inverter

The breaking of the induction motor leads to an energy flow back into DC link where the braking chopper and resistor limits the voltage rise and converts energy into heat. This method is not appropriate for high power induction motors where conversion of energy into the heat could last very short period of time. A better way for realization of induction motor breaking is application of an inverter on the drive side with line side step-up inverter and DC link between them as shown in Fig. 2.

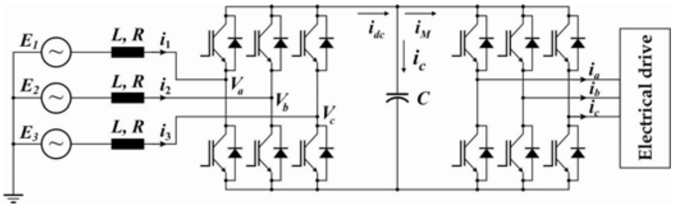

Fig.2. Active front end inverter topology with line-side inverter, DC-link and DC-AC drive inverter

On that way the recuperation energy is feeded back into the mains by a line side inverter in combination with a line side choke. The AC/DC converters become very important part of an AC/DC/AC line interfacing converters in renewable and distorted energy systems. The advantages of such topology (AFE) are[4], [5]:

- bi-directional power flow,
- sinusoidal current waveform,
- high input power factor including unity power factor operation,
- control and stabilization of the DC-link voltage,
- low harmonic distortion of line current
- reduced size of line inductor
- operation under line voltage distortion

Power factor can be controlled by phase angle between voltage and current waveform (lagging and leading power factor). The problem that may occur with AFE is high frequency harmonics which are function of the switching frequency. On that basis harmonics should be filtered. The complexity of the control for the active front end is comparable with the complexity of the field oriented control of the inverter for the motor. The line side and motor side inverter sections are thereby almost stressed by switching losses in the same amount.

II. SYSTEM DESCRIPTION

A. Mathematical model of Voltage-Source PWM Rectifier

To design control system and simulation model, it is necessary to define mathematical model of the Voltage Source Converter (VSC). As we mentioned before the VSC consists of IGBT module, which consists of six transistors and parallel connected freewheeling diodes. However, it is difficult to

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include all nonlinearities of IGBT module, and therefore following assumptions have been taken into considerations:

- transistors are assumed to be ideal switches
- time delay between control signals and IGBT module is neglected,
- transistor switching off time delay is zero,
- no switching loses.

Also, AC-side has been simplified as follows:

- symmetrical line voltages
- internal resistance of voltage supplies and wires resistance is zero,
- negligible small supply inductance
- ideal VSC input choke

The steady state characteristics as well as differential equations describing the dynamics of the front-end rectifier can be obtained independent of an inverter and motor load. This is because the DC-link voltage can be viewed as a voltage source. If V_{dc} is maintained constant for the full operating range, the terminal voltage remains unaffected during any electrical drive operation. The three-phase line voltages are shown in Eq. 1:

$$E_1 = E_m \sin(\omega t)$$
$$E_2 = E_m \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{1}$$
$$E_3 = E_m \sin\left(\omega t - \frac{4\pi}{3}\right)$$

and since there is no neutral connection we obtain Eq. 2:

$$I_1 + I_2 + I_3 = 0 \tag{2}$$

where E_{123} and I_{123} are line voltages and currents.

The rectifier is able to control magnitude and phase of PWM voltages V_{abc} irrespective of line voltages E_{123}. The dynamic equations for each phase can be written as [6]:

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + R\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \begin{bmatrix} V_{a0} \\ V_{b0} \\ V_{c0} \end{bmatrix} \tag{3}$$

In synchronous rotating dq reference frame Equations 4 and 5 represent the dynamic d-q model of an active front end inverter in a reference frame rotating at an angular speed of ω.

$$L\frac{di_{qe}}{dt} = E_{qe} - \omega L i_{de} - R i_{qe} - V_{qe} \tag{4}$$

$$L\frac{di_{de}}{dt} = E_{de} + \omega L i_{qe} - R i_{de} - V_{de} \tag{5}$$

To completely define system dynamics the DC side of the three-phase PWM rectifier can be expressed by Eq. 6:

$$i_{dc} = C\frac{dV_{dc}}{dt} + i_M \tag{6}$$

where, i_{dc} is the total dc-link current supplied by the rectifier, while i_M is the load-side DC current which is the result of induction motor operation.

The voltage components E_{qe} and E_{de} are computed from source voltages, E_1, E_2, and E_3. Since line voltages are known, the angular frequency, ω, can be easily estimated. The PWM voltages V_{qe} and V_{de} are the two inputs to the system which are generated using the sine-triangle PWM controller. L and R represent series impedance.

Eq. 4 and Eq. 5 shows that d-q current is related with both coupling voltages $\omega L i_q$ and $\omega L i_d$, and main voltage E_d and E_q, besides the influence of PWM voltage V_{qe} and V_{de}. Voltage V_{qe} and V_{de} are the inputs, controlled in such a way as to generate desired currents. Now new variables V'_{qe} and V'_{de} are defined,

$$V_{qe} = -V'_{qe} - \omega L i_{qe} + E_{qe} \tag{7}$$

$$V_{de} = -V'_{de} + \omega L i_{de} + E_{de} \tag{8}$$

So that the new system dynamic equations become,

$$L\frac{di_{qe}}{dt} = -i_{qe}R + V'_{qe} \tag{9}$$

$$L\frac{di_{de}}{dt} = -i_{de}R + V'_{de} \tag{10}$$

In Eq. 9 and Eq. 10 two axis current are totally decoupled because V'_{qe} and V'_{de} are only related with i_{qe} and i_{de} respectively. On this way we eliminate the coupling between two current components. To ensure constant DC-link voltage a simple proportional-integral (PI) controller is applied to the DC-link voltage error, resulting in the current reference command $i^*_{d\_e}$. Two simple proportional-integral (PI) controllers are adopted in the current regulation Fig. 3 and one proportional-integral (PI) controller in voltage regulation, Fig. 4.

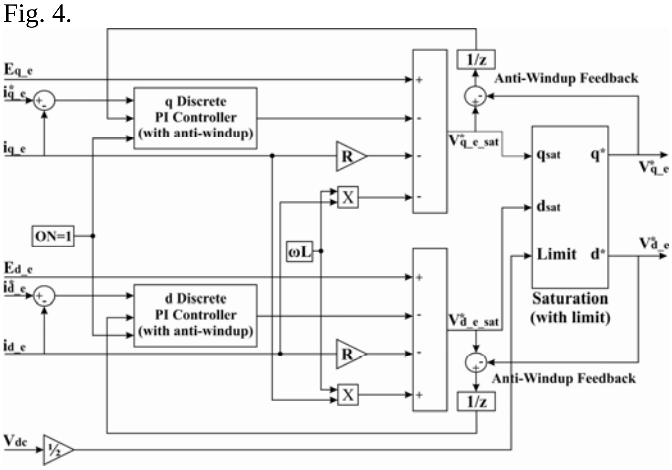

Fig. 3. Decoupled current controller with active damping

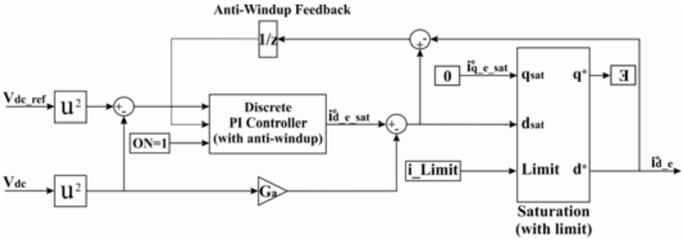

Fig. 4. Voltage controller with active damping

The control scheme of the PWM rectifier is based on a standard cascaded two-loop control scheme implemented in a d-q rotating frame: a fast control loop to control the current in the boost inductors and a much slower control loop to maintain constant DC-link voltage. The reference angle for the synchronous rotating d-q frame $\boldsymbol{\theta}$, is calculated, based on the three input phase voltages. For the effective PI control of

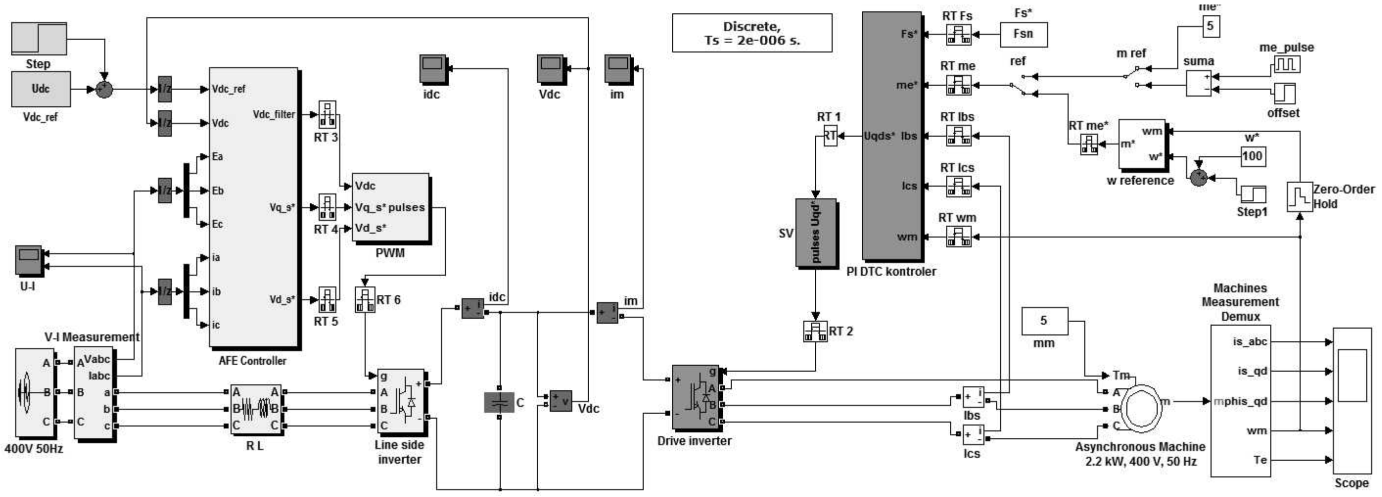

Fig. 5 Three-phase voltage source PWM rectifier with DTC induction drive mode

the DC-link voltage the linearization of the rectifier's output volatge contol loop has been carried out. The control variable (V^2_{dc}) has been taken into account instead the V_{dc}. On this way we eliminated the nonlinearity of PWM rectifier and made the linear PI voltage controller more robust. The line currents (i_1, i_2, i_3) are measured and transformed to the *d*-*q* reference frame in AFE controller block as it shown at Fig. 3. PI controllers for the *d* and *q* components of line current are identical and ωL terms are included to eliminate the coupling effect among the *d* and *q* components as it is shown at Fig. 5. Outputs of the line current PI controllers present *d* and *q* components of the voltage across the line inductance. Subtracting this voltage from the supply voltage gives the converter voltage from the AC side that is used to get the modulation signal for proper switching of six switching devices. Using this approach of control it is possible to control the output voltage of converter as well as the power factor of converter in the same time. To achieve unity power factor the reference of *q* current component need to be set on zero.

Over the years many control techniques have been adopted for the rectifier device in order to improve the AC power input power factor and reform the input current shape. The pulse-with modulation techniques include sinusoidal pulse-width modulation (SPWM), space vector pulse-width modulation (SVPWM), delta modulation techniques. According to traditional SPWM, the SVPWM has characteristic of high utilization rate of DC supply voltage and fast dynamic response [7], [8]. The current control strategies for voltage source converter on line side with PWM control scheme for three phase rectifier are used in this paper. On the load side the Direct Torque Control (DTC) of the motor is used as a control scheme.

III. SIMULATION RESULTS

According to the analysis above, the simulation model of whole system is built based on Matlab/Simulink and shown on Fig. 5. The whole system behavior is simulated as a discrete control system. The main parameters of the simulated circuit are given as following: Input phase to phase voltage is 400 V/50 Hz where the AC source is an ideal balanced three-phase voltage source. The inductance of AC side filter reactor L is 2.4 mH the AC side resistance R is 0.05 Ω, the DC side output capacitor C is 360 µF, the DC voltage is set to 513 V and the switching frequency is set to 10 kHz, nominal motor power 2,2 kW, nominal speed 302 rad/s, nominal torque 6.67 Nm and nominal motor current 5,2 A.

The induction machine is initially running at a constant speed reference 100 rad/s and under a 5 Nm load regime. In 0,5 s, we apply a rated speed reference 200 rad/s under 5Nm load, Fig. 6. Changing the speed reference corresponds to a step up speed perturbation. This is motor mode of induction machine when energy flows from line side to load side.

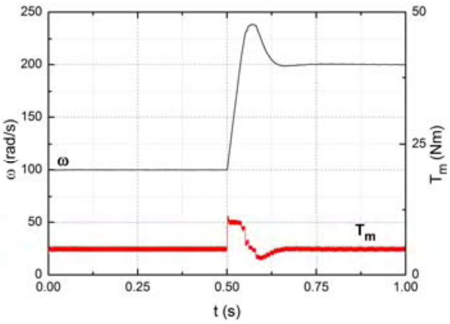

Fig. 6. Motoring mode: Reference speed and motor load

Because of unity power factor the line voltages and currents are in phase as it is shown on Fig. 7.

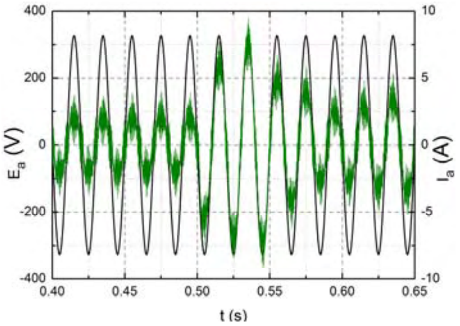

Fig. 7. Motoring mode: The waveform of A phase input voltage and current (unity power factor)

During this simulation voltage in DC-link V_{dc} was constant with small peak in 0,5 s, Fig. 8.

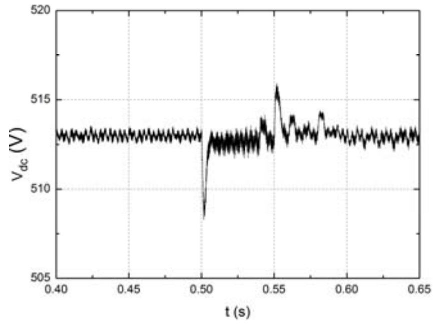

Fig. 8. Motoring mode: The waveform of DC output voltage

In second case the induction machine is initially running at a constant speed reference of 100 rad/s but with -5 Nm load regime. In 0.5 s we apply a rated speed reference 200 rad/s under the same load regime, Fig. 9. This corresponds to the regenerative mode of induction machine. On this way energy goes from induction machine to line side through the DC-link.

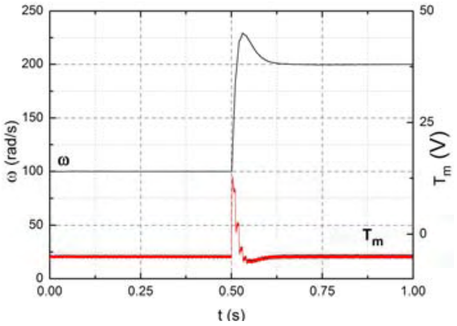

Fig. 9. Generating mode: Reference speed and motor load

The unity power factor in regenerative mode is shown at Fig. 10.

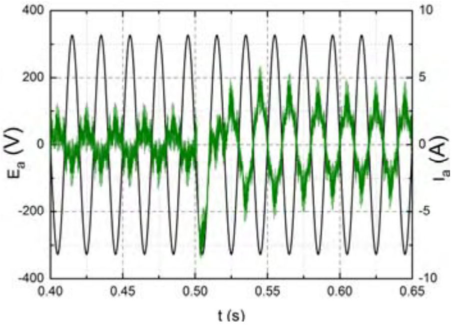

Fig. 10. Generating mode: The waveform of A phase input voltage and current (unity power factor)

Also the V_{dc} voltage was constant with small peak in 0,5 s, Fig. 11.

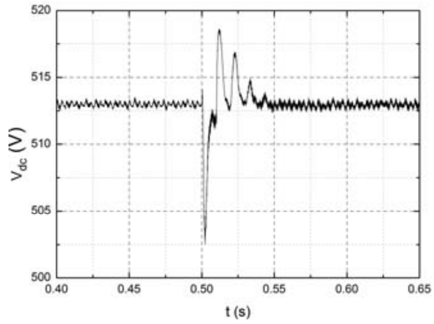

Fig. 11. Generating mode: The waveform of DC output voltage

IV. CONCLUSION

The efficiency and recuperation possibilities of AFE topologies become very important aspects in electric drives because of the possibility of bi-directional power flow, sinusoidal current waveform, high input power factor, control and stabilization of the DC-link voltage and low harmonic distortion of line current. A simple unity power factor of AFE rectifier and its application in electrical drives is introduced in this paper. Simulation result shows that unity power factor is achieved in both working mode of induction machine. Constant dc voltage reaches the requirement of design.

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REFERENCES

[1] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, Control in Power Electronics. Academic Press - USA, 2002.

[2] M. Lissere, P. Rodriguez, J. Guerrero, and R. Teodorescu, “Power electronics for pv energy systems integration,” 39th IEEE PESC, 15–19 June 2008, tutorial.

[3] M. P. Kazmierkowski, M. Jasinski, and H. C. Sorensen, “Ocean wave energy converters-wave dragon mw,” Przeglad Elektrotechniczny, vol. 84, no. 2, pp. 8–13, 2008.

[4] Ricardo Luiz Alves and Ivo Barbi, ”A New Hybrid High Power Factor Three-Phase Unidirectional Rectifier” Industrial Electronics, 2006 IEEE International Symposium on Volume 2, pp. 1046-1051, July 2006.

[5] Ye, Y., Kazerani, M., Quintana, V.H., “A Novel Modeling and Control Method for three-phase PWM converters”, Power Electronics Specialists Conference, 2001. PESC. IEEE 32nd Annual Volume 1, 17-21, pp.102-107, June 2001.

[6] Wang Xu, Huang Kaizheng, Yan Shijie, Xu Bin. “ Simulation of Three-phase Voltage Source PWM rectifier Based on Space Vector Modulation”. Control and Decision Conference, Chinese, IEEE, Pages: 1881-1884, 2008.

[7] Ian Wallace, Ashish Bendre, Jonathan P. Nord and Giri Venkataramanan,“A unity-power-factor three-phase PWM SCR rectifier for high-power application in the metal industry,” IEEE Transactions on Industry Applications, Vol. 38, No. 4, pp. 898-908, July/August 2002.

[8] Poh Chiang Loh and Donald Grahame Holmes, “A variable band universal flux/charge modulator for VSI and CSI modulation,” IEEE Transactions on Industry Applications, Vol. 38, No. 3, pp.695-705, May/June 2002.