Dynamic Braking in Induction Motor Adjustable Speed Drives

Nebojsa Mitrovic[1], Milutin Petronijevic[2], Vojkan Kostic[3] and Bojan Bankovic[4]

Abstract – **A voltage source PWM inverter with diode front-end rectifier is one of the most common power configurations used in modern variable speed AC drives. However, it allows only unidirectional power flow. Various alternative circuits can be used to recover the load energy and return it to power supply. This paper presents the most popular topology used in adjustable speed drive (ASD). The diode rectifier is replaced with PWM voltage source rectifier. This is already an industrially implemented technology and known as most successful active front end (AFE) solution in ASD if regenerative operation is needed.**

Keywords – **Adjustable speed drive, Active front end.**

I. INTRODUCTION

Today's adjustable speed drives (ASD) in the low and mid power range are normally based on the concept of variable voltage, variable frequency (VVVF). Fig.1 shows the basic concept of a single variable speed drive. The three-phase AC supply network is rectified. The DC capacitor, which links the supply rectifier to the inverter, assures that the inverter sees a constant DC voltage from which it generates the required supply voltage and frequency to the motor.

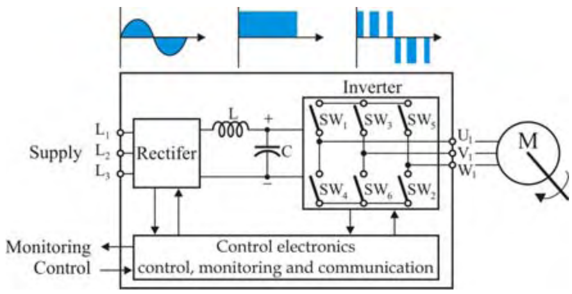

Fig. 1. Basic concept of a variable speed drive.

General classification divides induction motor control schemes into scalar and vector-based methods [1]. Opposite to scalar control, which allows control of only output voltage magnitude and frequency, the vector-based control methods enable control of instantaneous voltage, current and flux vectors. Type of the front end converter, regardless of the control schemes, depends on the power and torque requirements of the drive [2].

In order for an AC drive to operate in quadrant II or IV in speed-torque plane, rectifier must be able to deal with the electrical energy returned to the drive by the motor [3]. The typical pulse width modulated AC drive is not designed for regenerating power back into the three phase supply lines. Electrical energy returned by the motor can cause voltage in the DC link to become excessively high when added to existing supply voltage. Various drive components can be damaged by this excessive voltage. These regenerative conditions can occur when:

- quickly decelerating a high inertia load,
- controlling the speed of a load moving vertically downward (hoist, declining conveyor),
- a sudden drop in load torque occurs,
- the process requires repetitive acceleration and deceleration to a stop,
- controlling the speed of an unwind application.

In standard drives the rectifier is typically a 6-pulse diode rectifier only able to deliver power from the AC network to the DC bus but not vice versa. If the power flow changes as in two or four quadrant applications, the power fed by the process charges the DC capacitors and the DC bus voltage starts to rise. The capacitance is a relatively low value in an AC drive resulting in fast voltage rise, and the components of a frequency converter may only withstand voltage up to a certain specified level.

In order to prevent the DC bus voltage rising excessively, the inverter itself prevents the power flow from process to frequency converter. This is done by limiting the braking torque to keep a constant DC bus voltage level. This operation is called overvoltage control and it is a standard feature of most modern drives. However, this means that the braking profile of the machinery is not done according to the speed ramp specified by the user.

There are two technologies available to prevent the AC drive from reaching the trip level: Dynamic braking and active front end regeneration control [4,5]. Each technology has its own advantages and disadvantages.

II. DYNAMIC BRAKING

A dynamic brake consists of a chopper and a dynamic brake resistor. Fig.2 shows a simplified dynamic braking schematic. The chopper is the dynamic braking circuitry that senses rising DC bus voltage and shunts the excess energy to

[1]Nebojsa Mitrovic, University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: nebojsa.mitrovic@elfak.ni.ac.rs.
[2]Milutin Petronijevic, University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: milutin.petronijevic@elfak.ni.ac.rs.
[3]Vojkan Kostic, University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: vojkan.kostic@elfak.ni.ac.rs.
[4]Bojan Bankovic, University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: bojan.bankovic@elfak.ni.ac.rs.

the dynamic brake resistor. A chopper contains three significant power components: The chopper transistor is an IGBT. The chopper transistor is either ON or OFF, connecting the dynamic braking resistor to the DC bus and dissipating power, or isolating the resistor from the DC bus. The current rating of the chopper transistor determines the minimum resistance value used for the dynamic braking resistor. The chopper transistor voltage control regulates the voltage of the DC bus during regeneration. The dynamic braking resistor dissipates the regenerated energy in the form of heat.

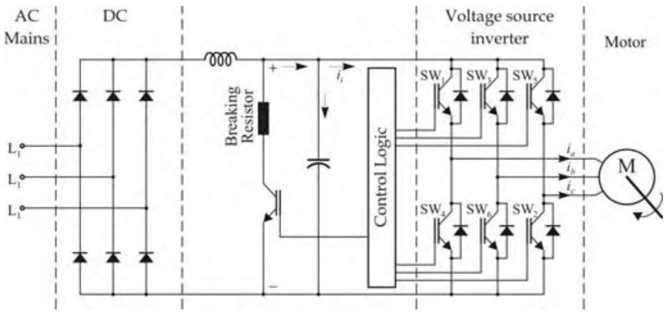

Fig. 2. Voltage source inverter with diode front end rectifier and dynamic brake module.

As a general rule, dynamic braking can be used when the need to dissipate regenerative energy is on an occasional or periodic basis. In general, the motor power rating, speed, torque, and details regarding the regenerative mode of operation will be needed in order to estimate what dynamic braking resistor value is needed. The peak regenerative power of the drive must be calculated in order to determine the maximum resistance value of the dynamic braking resistor [3].

The peak breaking power required to decelerate the load, according to equation (1) is:

$$P_b = \frac{J\,\omega_b(\omega_b - \omega_0)}{t_b} \quad (1)$$

where t_b represents total time of deceleration, ω_b and ω_0 initial and final speed in the process of braking.

The value of P_b can now be compared to the drive rating to determine if external braking module is needed. If peak braking power is 10% greater than rated drive power external braking module is recommended. Compare the peak braking power to that of the rated motor power, if the peak braking power is greater than 1.5 time that of the motor, then the deceleration time, needs to be increased so that the drive does not go into current limit.

Maximum dynamic brake resistance value can be calculated as:

$$R_{db} = \frac{V_{dc}}{P_b} \quad (2)$$

The choice of the dynamic brake resistance value should be less than the value calculated by equation (2). Once the maximum resistance value of the dynamic braking resistor current rating is known, the required rating of dynamic braking resistors can be determined. If a dynamic braking resistance value greater than the minimum imposed by the choice of the peak regenerative power is made and applied, the drive can trip off due to transient DC bus overvoltage problems. Once the approximate resistance value of the dynamic braking resistor is determined, the necessary power rating of the dynamic braking resistor can be calculated. The power rating of the dynamic braking resistor is estimated by applying what is known about the drive's motoring and regenerating modes of operation.

To calculate the average power dissipation the braking duty cycle must be determined. The percentage of time during an operating cycle (t_c) when braking occurs (t_b) is duty cycle ($\varepsilon = t_b/t_c$). Assuming the deceleration rate is linear, average power is calculated as follows:

$$P_{av} = \frac{t_b}{t_c}\,\frac{P_b}{2}\,\frac{\omega_b + \omega_0}{\omega_b} \quad (3)$$

Steady state power dissipation capacity of dynamic brake resistors must be greater than that average.

Fig.3a) shows the experimental results (DC voltage and chopper current) for the variable frequency drive with braking module in DC link and external braking resistor, under a step change of induction motor load in regenerative regime. Danfoss frequency (series VLT 5000) converter is used in experimental set-up. For the supply voltage of 400 V, DC link voltage is about 540 V.

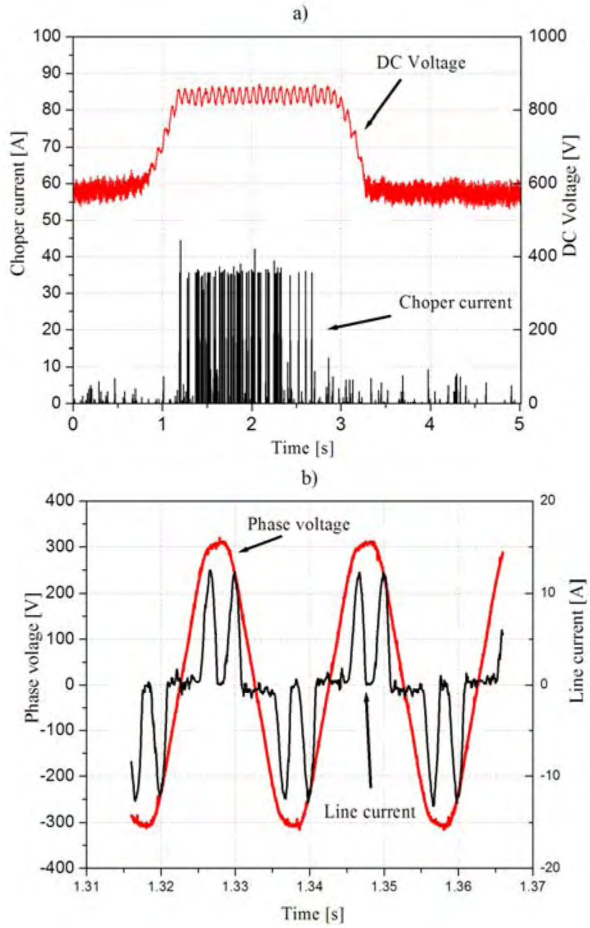

Fig. 3. a) DC voltage and chopper current, b) line voltage and current.

When negative load torque is applied, DC link voltage rises. The chopper transistor voltage control regulates the voltage of the DC bus during regeneration to near 800 V allowing current flow in the resistor. Regenerative energy is then realised into heat. After the end of the regenerative period, DC voltage returns to a value that corresponds to a motor regime. The Fig.3b) shows the line voltage and current at the input of the diode rectifier.

A voltage source PWM inverter with diode front-end rectifier is one of the most common power configurations used in modem variable speed AC drives, (Fig. 2). An uncontrolled diode rectifier has the advantage of being simple, robust, and low cost. However, it allows only unidirectional power flow. Therefore, energy returned from the motor must be dissipated on a power resistor controlled by a chopper connected across the dc link. A further restriction is that the maximum motor output voltage is always less than the supply voltage.

III. Active Front End Rectifier

Various alternative circuits can be used to recover the load energy and return it to power supply. One such scheme is shown in Fig. 4 and presents the most popular topology used in ASD. The diode rectifier is replaced with PWM voltage source rectifier. This is already an industrially implemented technology and known as most successful active front end (AFE) solution in ASD if regenerative operation is needed (e.g. for lowering the load in crane) and therefore was chosen by most global companies: Siemens, ABB, and others.

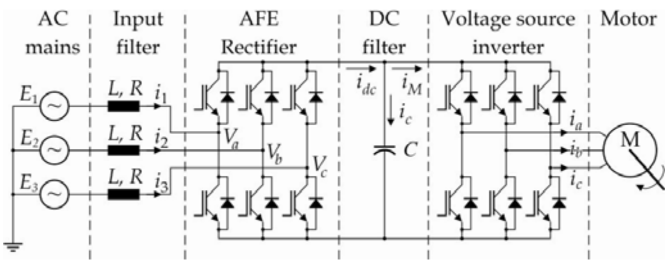

Fig. 4. Active front end inverter topology.

The term Active Front End Inverter 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. But, during regeneration it can also be operated as an inverter, feeding power back to the line. The line-side converter is popularly referred to as a PWM rectifier in the literature. This is due to the fact that, with active switches, the rectifier can be switched using a suitable pulse width modulation technique.

The PWM rectifier basically operates as a boost chopper with AC voltage at the input, but DC voltage at the output. The intermediate DC-link voltage should be higher than the peak of the supply voltage. The required DC-link voltage needs be maintained constant during rectifier as well as inverter operation of the line side converter. The ripple in DC link voltage can be reduced using an appropriately sized capacitor bank. The AFE inverter topology for a motor drive application, as shown in Fig.4, has two three-phase, two-level PWM converters, one on the line side, and another on the load side. The configuration uses 12 controllable switches. The line-side converter is connected to the utility through inductor. The inductor is needed for boost operation of the line-side converter.

For a constant dc-link voltage, the IGBTs in the line-side converter are switched to produce three-phase PWM voltages at *a*, *b*, and *c* input terminals. The line-side PWM voltages, generated in this way, control the line currents to the desired value. When DC link voltage drops below the reference value, the feed-back diodes carry the capacitor charging currents, and bring the DC-link voltage back to reference value.

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 inverter is thus connected to the voltage source, whose terminal voltage V_{dc}, remains unaffected by any normal inverter and motor operation [6].

Furthermore, as shown in Fig.4, the rectifier can also be viewed as connected to the voltage source V_{dc}. Thus, the rectifier is able to control magnitude and phase of PWM voltages V_{abc} irrespective of line voltages E_{123}.

The simple proportional-integral (PI) controllers are adopted in the current and voltage regulation. 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 θ, is calculated, based on the three input phase voltages.

For the current control loop *d-q* synchronously rotating reference frame with the fundamental supply voltage frequency is used [7]. The line currents (i_1, i_2, i_3) are measured and transformed to the *d-q* reference frame, Fig.5.

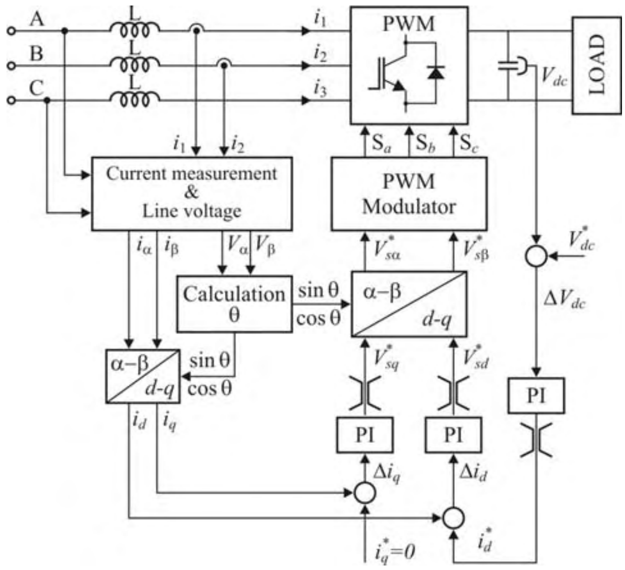

Fig. 5. Simplified block diagram of the AFE.

To get information about the position of the line voltage vector PLL (phase locked loop) is implemented. PI controllers for the *d*-*q* components of line current are identical and ω*L* terms are included to eliminate the coupling effect among the *d* and *q* components [7]. 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.

The main task of the sinusoidal front end is to operate with the sinusoidal line current; so *d* and *q* components of the line current reference are DC values. 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.

Different tests have been performed on the AFE inverter system to show some of the capabilities: simovert masterdrives 3-phase, 380-460V, 260A, inverter nominal power rating 132 kW. The measurements are done at steady-state operation. During experiments, the DC link voltage is boosted to 650 V. The first test is rectifier system operation when the induction machine operates as motor, Fig.6a), and second test is regenerative operation during regenerative operation, Fig.6.b).

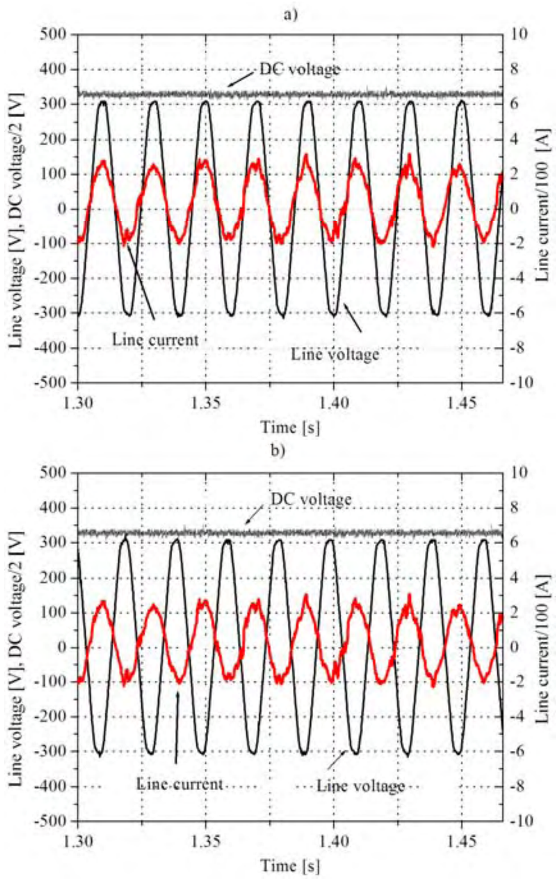

Fig. 6. Waveforms under steady-state operation: Line voltage, line current and dc link voltage a) motor operation, b) generator operation.

Both figures show the measured line currents, line voltages and DC voltage. It can be observed a high stationary performance both in motor and generator operation. The line current is nearly a sine wave with unity power factor while DC voltage is unchanged.

IV. Conclusion

The application of squirrel cage induction motors supplied from the frequency converters (also known as adjustable speed drive - ASD) have become the standard solution for the modern drives applications. However, the standard configuration of the inverter can not be used for some drives primarily due to regenerative operation, which in some cases may be intermittent and continuous.

This paper describes the solutions that are commonly used in modern crane drives. In case that it is a casual recuperating the dynamic braking is used. If continious regeneretation occur active front end rectifier capable to returning energy into the supply network is used. In addition active front end rectifier keeps the network current sinusoidal and a unity power factor by controlling the drive input to produce sinusoidal current without the harmonic components associated with conventional rectifiers.

Acknowledgement

This paper is supported by Project Grant III4400X (2011-2014) financed by Ministry of Education and Science, Republic of Serbia.”

References

[1] M. Petronijevic, B. Veselic, N. Mitrovic, V. Kostic & B. Jeftenic, "Comparative Study of Unsymmetrical Voltage Sag Effects on Adjustable Speed Induction Motor Drives", Electric Power Applications, IET , vol.5, no.5, pp.432-442, May 2011

[2] B. Jeftenic, M. Bebic, S. Statkic, "Controlled multi-motor drives", International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2006, Taormina (Sicily) - ITALY, 23-26 May 2006 , pp. 1392-1398.

[3] Rockwell Automation, Load Sharing for the 1336 PLUS II AC Drive, *Publication number* 1336E-WP001A-EN-P, June 2000.

[4] N. Mitrovic, M. Petronijevic, V. Kostic, B. Bankovic, "Active Front End Converter in Common DC Bus Multidrive Application", XLVI Inter. Conf. ICEST 2011, Serbia, Nis, June 29 - July 1, 2011, Proc. Vol.3, pp. 989-992, 2011.

[5] Rashid H., *Power Electronics Handbook*, Academic Press, San Diego, 2001.

[6] K. Hartani, Y. Miloud, "Control Strategy for Three Phase Voltage Source PWM Rectifier Based on the Space Vector Modulation", Advances in Electrical and Computer Eng., Vol.10, Issue 3, pp. 61-65, 2010.

[7] M. Odavic, Z. Jakopovic, F. Kolonic, "Sinusoidal Active Front End under the Condition of Supply Distortion", AUTOMATIKA 46(2005) 3–4, pp.135–141, 2005.