AC-AC CONVERTER FOR INDUCTION MOTOR APPLICATION

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Abstract: The goal of this paper is to present the topology, the control design and the experimental results of the 37 kW high performance quasi direct ac-ac converter prototype. The control algorithms and the strategy adopted in this paper are well suited for the ac drives application area. The complete ac-ac system is presented, but the main research interest was focused on the input conversion stage with the scope of meeting the following specifications: unity power factor operation; low input current harmonics; regeneration capability; reduced size of reactive components; full exploitation of the supply voltage. Although the output power inverter determines the overall drive performance, it has been treated only marginally since the conventional field oriented control was used. The overall system control has been designed to tightly balance the power flow in the system. Therefore, a small plastic film capacitor was used instead of the big electrolytic one, as with indirect ac-ac converters. The feed-forward load component has been added to the current reference of the source converter and thus, improving performances were obtained during the transients because of the fast control response to load changes (the feed-forward component was introduced in the inner control loop of the system). The stationary and transitory performances of the ac-ac converter system are shown through the experimental results, and so are the motor and regenerative operations.

Keywords: power-balancing control, pulsewidth modulation converter–inverter system, AC drives, regenerative applications

1. INTRODUCTION

In case of nonlinear loads, the quality of current is the consumer's own responsibility [1]. On the other hand, for harmonics producing loads, the quality of current depends upon amount of load, resulting in a maximum distortion in current at light loads and highest magnitude of the harmonics current at full load.

In many countries the induction machines are used in various places: industry (cement, pulp and paper mills, chemical, petroleum, manufacturing mining and metals, marine, robotics and so on) and applications (compressors, fans, blowers, pumps, heating ventilating and air conditioning systems). A large proportion of electrical energy (about 60%) [2] is consumed by induction motors (IM). One drawback of conventional variable speed drives is the large content of low frequent line-current harmonics due to the diode rectifer on the line side. From the quality terms point of view, the researching focalization upon this type of variable speed drives is essential in order to limit the losses produced by the current harmonics in the utility grid.

Passive filters, twelve-pulse operation, multi-level rectifiers or force commutated rectifiers (PWM rectifier) solutions are available to solve these problems.

A force commutated converter can have much faster control over its input current and output voltage, which gives it better performance. This property is useful in servo applications with high performance requirements. The use of the force-commutated PWM source converters is also related to attaining of the bi-directional power flow and unity power factor, respectively. The first approaches in the ac/ac conversion with PWM modulators were done in [3]-[4]. Later, the power balance concept was introduced [6]. The load feedforward was introduced by Sul et al. [7] in order to increase the dynamic response of the bus voltage to changes in load. A distinctive development can also be observed in the techniques which provide a network synchronization and unity displacement factor operation of the input converter. The first approach by Ooi [5] used an input voltage template signal derived from the line to line voltages. An advanced technique, which has been introduced later, is very similar to the field oriented principle of an ac machine, where the components responsible for the transfer of active and reactive power are derived by using the information of the network angular electrical speed. This technique was studied in the many research works [8]-[9]. Various power factor correction (PFC) schemes have been proposed to improve the load power factor in the single phase appliances. The situation is rather different in PWM voltage source inverters (VSI) for the ac drive application. Since these are typically rated for much higher power, the harmonic distortion is also higher and, consequently their impact on the utility is stronger. Therefore, it is desired that input ac/dc converter would operate with near unity power factor and the low harmonic distortion. In other words, the currents drawn from the lines should be sinusoidal. Furthermore, the regeneration capability of PWM VSI becomes quite a mandatory requirement. Thus, the requirements on the ideal input ac/dc conversion stage can be summarized as follows: unity power factor operation; low input current harmonics; regeneration capability; reduced size of reactive components; full exploitation of the supply voltage.

2. QUASI SINUSOIDAL AC-AC CONVERTER

2.1 The power stage

The power stage of the three-phase voltage ac-ac converter system contains three-phase input boost inductor, a force-commutated rectifier and a force-commutated inverter connected through a common dc-link (Fig. 1). The overall system control is designed to tightly balance the power flow in the system. Therefore, a small plastic film capacitor was used in dc link instead of the big electrolytic one. The properties of this combination are: the line-side converter operates to give sinusoidal line currents, the dc-link voltage is higher than the peak main voltage, the dc-link voltage is regulated by controlling the power flow to the ac grid and the inverter operates on the boosted dc-link, making it possible to increase the output power of a connected machine over its rated power, and the braking energy can be fed back to the power grid instead of just wasting it in a braking resistor. The input boost inductor, *L*, is designed from the THD factor point of view. Therefore, the input current THD factor is constrained to be less than 5% at the full load. The DC link capacitor, *C*, provides a decoupling function between the grid side and load side, respectively.

2.2. The control structure

The structure of the AC/AC converter control system is shown in Fig. 1. The control structure of the AC-AC converter is in cascaded manner, with the internal current loop and dc link external voltage loop. The control of the ac-ac converter prototype was implemented by using two control boards (based on the dSMC 101 digital signal processors-DSP), that communicate each other through the Synchronous Serial Interface (SSI). On the basis of a DC voltage reference V^*_{dc}, dc voltage feedback signal (V_{dc}), ac input voltages (V_{ab} and V_{bc}), current feedback signals (I_a, I_b for supply converter, and I_u, I_v for the load converter), speed reference, flux reference, the magnetizing current, and load power signal (obtained through Synchronous Serial Interface – SSI), the DSP software operates the ac-ac control (voltage, current, flux and speed loops) system and generates the firing gate signals to the corresponding PWM modulator. The task of the voltage and the current regulation has been accomplished by means of the Proportional-Integral (PI) controller, because of its good steady-state and dynamic behavior with the ac-dc converter. It is important to underline that the PI controller performances are parameters sensitive, because of its design procedure, based on the DC bus capacitor and inductor values. However, in these specific applications, the system parameters values

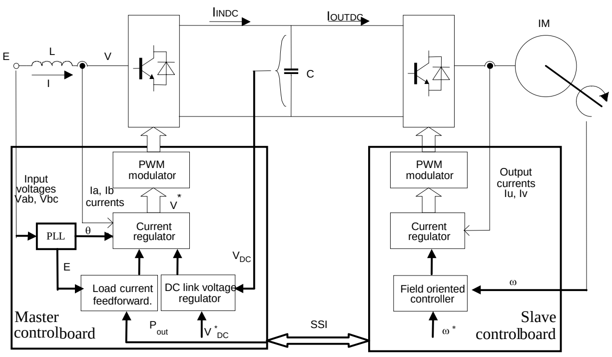

Fig. 1 Control block diagram of the AC-AC converter.

are known with reasonable accuracy. A phase locked loop (PLL) ensures synchronization of the reference frame with the source phase voltages by maintaining their *d* component at zero (E_d=0) through a PI regulator.

3. THE MODEL OF THE AC-DC CONVERTER

The present paper is only focused on AC/DC stage. Although, the output power inverter determines the overall drive performance, it is treated only marginally since the conventional field orientation control was used [10]. In order to design the AC/DC control it is necessary to write the differential equations of the system. By aligning the *q* axis with the main voltage vector $\vec{E}$, the components in the *q*, *d* synchronous reference frame can be obtained:

$$\vec{E} = E_Q + j \cdot E_D \text{, with } E_D = 0 . \tag{1}$$

The current model in the *q -d* reference frame is represented by the following first-order differential equations:

$$\begin{aligned} \frac{dI_D}{dt} + \omega \cdot I_Q &= -\frac{1}{L} \cdot V_D + \frac{1}{L} \cdot E_D \\ \frac{dI_Q}{dt} - \omega \cdot I_D &= -\frac{1}{L} \cdot V_Q + \frac{1}{L} \cdot E_Q \end{aligned} \tag{2}$$

where E_Q and E_D are the *q-d* mains voltage components, I_Q and I_D are the *q-d* line current components, *L* is the line inductance, V_D and V_Q are the voltage of the input AC-DC supply converter, that differ from the E_Q and E_D voltages because of the boost inductor, like shown also in Fig. 1. The decoupled AC-DC converter vectorial equation is:

$$\vec{E} = L \cdot \frac{d\vec{I}}{dt} + \vec{V} \tag{3}$$

It is necessary to find the relation between the I_Q - I_D currents and the DC link voltage, V_{dc} (the system output). The dc link input power of the AC-DC converter:

$$P_{INDC} = V_{dc} I_{INDC} \tag{4}$$

where I_{INDC} is the dc link input current (Fig.1).
The ac power of the AC-DC supply converter, in *q-d* reference frame, is as follows:

$$P_{AC} = \frac{3}{2} \cdot \left(V_D \cdot I_D + V_Q \cdot I_Q \right) \tag{5}$$

Moreover, the equation between the capacitor current and voltage, making reference to the variable definitions depicted in Fig. 1, is

$$C \cdot \frac{dV_{dc}}{dt} = I_{INDC} - I_{OUTDC} \tag{6}$$

Therefore, equaling the P_{INDC} and P_{AC} powers (in order to obtain I_{INDC}), the following equation is obtained, that expresses the connection between the currents I_Q, I_D and the voltage V_{dc}:

$$\frac{dV_{dc}}{dt} = \frac{3}{2} \cdot \frac{V_D \cdot I_D + V_Q \cdot I_Q}{C \cdot V_{dc}} - \frac{I_{OUTDC}}{C} \tag{7}$$

The modulation system has been modeled in a simplified way, that is the ideal transfer function between the *q-d* reference voltages, V_Q^*, V_D^*, and those applied to the converter, V_Q, V_D, is unitary.

4. THE CURRENT CONTROL OF THE AC-DC CONVERTER

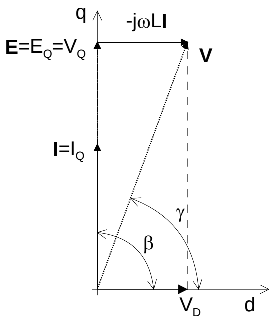

Fig. 2 Input voltage and current supply vectors in the synchronously reference frame at unitary power factor operation

The scope of the current loop is to impose the sinusoidal current absorption from the supply with unitary power factor. The current control system has been implemented in synchronously, *q-d* reference frame. By using synchronous rotating-frame current regulators in the source (ac-dc) converter side, the active and reactive power can be controlled independently.

In order to impose a unitary power factor (cos(ϕ)=1, where ϕ is the angle between the current and the voltage supply), it is enough to set up the direct current reference, I_D*, to zero. In such case, the current vector $\vec{I}$ lies on the *q* axis and therefore, it is in phase with the $\vec{E}$ vector, like in Fig. 2. Clearly, if a cos(ϕ)≠1 is desired, in order to absorb a reactive power from the supply, it will be enough to act on the I_D* value.

4.1 Design of the current PI controller with direct compensation of the disturbance and decoupling of the *q-d* axes.

In order to improve the converter's performances, it is necessary to decouple the two axes. Moreover, the mains voltages components E_D and E_Q represent the disturbance signals that act on the system. Such voltages have been already measured from the system because they serve for the reference frame rotational angle. Therefore, it is possible to perform the direct compensation of such disturbs. The *d-q* axes decoupling is obtained by canceling the ($\omega \cdot L$) signal, that acts on *d* axis, and the (- $\omega \cdot L$) one, that acts on *q* axis [10]. Due to the *d-q* axes decoupling, the transfer function of the system under control, P_{dis}(s), will become an integrator:

$$P_{dis}(s) = \frac{V_Q^*}{I_Q^*} = -\frac{1}{Ls} \tag{8}$$

Therefore, theoretically speaking, a pure proportional controller could be used since the transitory null error is already assured from the integral system under control. But in order to have a robust control system to eventual disturbs, the use of a proportional-integral controller is preferred.

The system under control, in the hypothesis that the *q*, *d* axes are decoupled and with direct compensation of the disturbance, turns out:

$$P_{dis}(s) = -\frac{1}{Ls} \tag{9}$$

The transfer function of the PI controller:

$$C_{PIc}(s) = K_{pc}\left(1 + \frac{1}{T_{ic}s}\right) \tag{10}$$

The calculation of the PI controller coefficients, K_{pc} (proportional gain) and T_{ic} (integral time), is done imposing the phase margin ϕ_{mc} (in radian) and the bandwidth ω_c (in radian per second).

Imposing these two conditions, the following relations for K_{pc} and T_{ic} are obtained:

$$\begin{cases} T_{ic} = \dfrac{1}{\omega_c \cdot \tan(\phi_c - \phi_{mc})} \\ K_{pc} = \dfrac{-T_{ic} \cdot \omega_c}{M \cdot \sqrt{1 + (T_{ic} \cdot \omega_c)^2}} \end{cases} \tag{11}$$

where M and ϕ_c are the module and the phase (in radian) of the system P_{dis}(s) under control.

In this case, $M = \frac{1}{L\omega_c}$ and $\phi_c = -\frac{\pi}{2}$. The negative sign in the formulas derives from the fact that the gain of the system under control is negative.

5. EXPERIMENTAL RESULTS

The control system emulation based on SIEI RVRUY-37 board uses SICAN 101 dSMC, VECANA DSPs and C166 μC. The capability to provide simultaneous sampling on all channels is mandatory for this application. Complementary external boards implement signal conditioning and protection circuitry. The powerful SICAN 101 DSP provides fixed-point arithmetic and high computing power. The power stage of the 37-kW prototype unit is based on two 1200V IGBTs three-phase voltage power modules followed by SKHI drive types from Semikron. The power semiconductor switches are operated with T_s=125μs switching time. The capacitor bank has two parallel connected 500μF film capacitors with 900V dc rating voltage. The line inductance of the converter has 0,5 mH value. By choosing the cut-off frequency f_c=600Hz and the phase margin ϕ_{mc}=1,047 rad, the following current regulator parameters have been obtained: T_{ic}=0.4594 msec, K_{pc}=-1,632. To show the effectiveness of the proposed control strategy for the ac-ac converter, the stationary and transient performances are presented (Figs.3-8). Less than 5% current THD factor (under rated power level) was obtained.

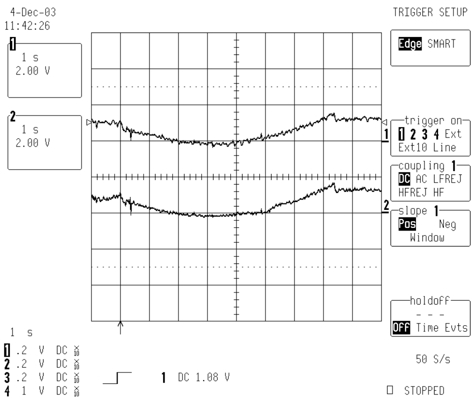

Fig. 3 Reference and actual *q* axis current waveforms. Top trace (Ch.1): the *q* axis current reference, I^*_q 75A/div. Bottom trace (Ch.2): the actual *q* axis current, I_q.

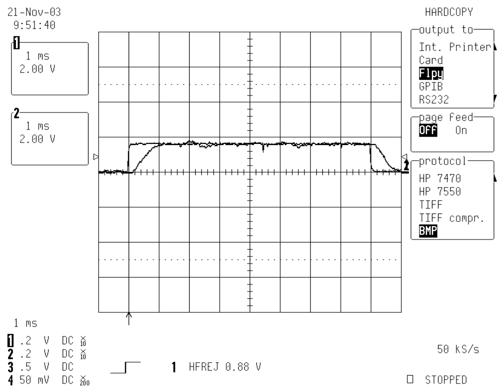

Fig. 4 Reference and actual *d* axis current waveforms. Ch.1: the *d* axis current reference 37A/div. Ch.2: the actual *d* axis current.

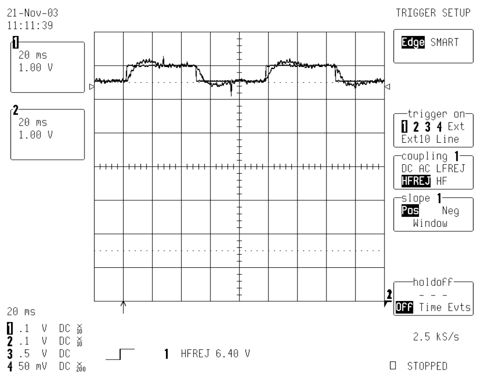

Fig. 5 Reference and actual dc link voltage waveforms. Ch.1: the dc link voltage reference, V*DC. Ch.2: the actual dc link voltage, VDC, 230V/div.

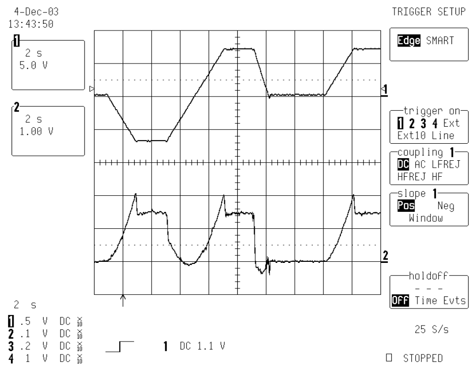

Fig. 6 The induction motor speed, ωr: Ch1 – 705rpm/div, Ch2 – The inverter output power Pout, 23kW/div.

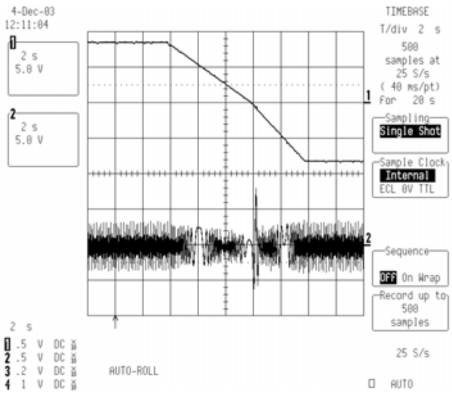

Fig.7 The induction motor speed: Ch1 – 705rpm/div, Ch2 – The inverter output current IU, 75A/div.

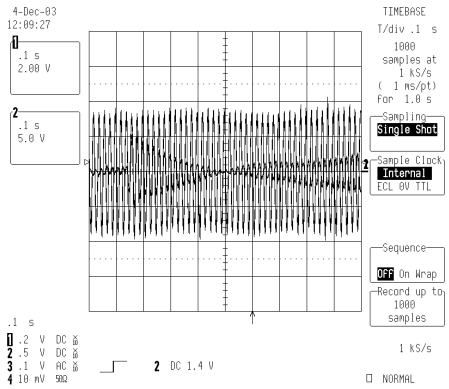

Fig. 8 System traces showing unity power factor operation of system during regeneration and motor operations. Ch A: V_PHASE_A (converter input phase voltage) 178 V/div, Ch. B: IA (input line current) 75 A/div.

6. CONCLUSIONS

The study on an AC-AC converter prototype for induction motor application has been carried out in this paper. PI based control technique has been developed to provide suitable compensation of line current harmonics and near unitary power factor. It has been found that the voltage controller well responds for load changes and provides a regulated DC voltage. The dynamic response of voltage controller has been shown under the load changes from one value to another value. The increase in the ac-ac converter power response makes possible the reduction of the DC link capacitor size without systems' stability disturbing. The experimental results on the 37-kW, 400V prototype unit confirm the good load current regulation, the unity power factor operation of the source converter, power reversibility capabilities as well as the good power matching control. Through a proper control sinusoidal input current, a nearly unity power factor (0,998), bi-directional power flow, small (up to 5%) ripple in the dc-link voltage in any operating conditions, disturbance compensation capability, fast control response and high quality balanced three-phase output voltages were obtained.

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