A CONTROL METHOD FOR VOLTAGE SOURCE INVERTER WITHOUT DC LINK CAPACITOR

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***Abstract* – Voltage source inverter plays an important role in modern industry. Conventional voltage source inverter has a large electrolytic capacitor as energy store element in order to keep the dc link voltage constant. However, a large electrolytic capacitor increases the input current distortion. Replacing the large electrolytic capacitor by a small film capacitor, the input current quality is improved but the output currents are distorted by low order harmonics. This paper proposes a simple current control method for a voltage source inverter without the use of a large electrolytic capacitor in the dc link in order to compensate the low order harmonics in the output currents. The proposed current control scheme employs just one PI regulator and since that the space vector modulation is used in this control, the switching frequency of the converter is kept constant.**

***Keywords* – voltage source inverter, current control, LC filter, modulation index.**

I. INTRODUCTION

The modern industries commonly use voltage source converters for adjustable speed electrical drives. Most of the frequency converters are voltage source inverters and consist of a diode rectifier, a dc link with electrolytic capacitor as energy store element and a self-commuted converter with IGBT and anti-paralleled fast recovery diodes. Although this kind of converter has a mature technology and robustness, the presence of a large electrolytic capacitor in dc link causes a high-distorted input current with THD that can be over of 120%. This high amount of harmonics distorts the line voltage and it may cause malfunction on sensible equipments. Since power quality is a big concern today, it is very important do not degrade the voltage of the utility. Several power quality standards like IEEE519 and EN50160 provide guidelines limits on the amount of the harmonic current and limit the voltage distortion that the harmonic current can produce. Depending on the harmonic specification, it may be required relatively bulk and expensive AC line reactors in order to reduce the THD of the input current. Besides that, the electrolytic capacitor is bulk, expensive and also has a short lifetime compared with others nonelectrolytic capacitors.

Two kinds of power converter have received attention as a possible alternative for voltage source converter: the matrix converter [1] and indirect ac/dc/ac converter [3]. The matrix converter, as shown in Fig. 1, can perform the power conversion directly from AC power source to the load without any intermediate DC link and it is able to operate in four quadrant operation, unity input power factor, voltage and current sinusoidal waveforms with only high order harmonics in both line and load side respectively. The drawback is that matrix converter needs a large amount of unidectional switches to implement its bidirectional switches which makes the control and protection of these switches very complex [2]. In addtion, it is necessary a three-phase input filter to remove the high switching frequency harmonics. The indirect ac/dc/ac converter, as shown in Fig. 2, consists of a PWM rectifier-inverter with a reduced capacitor in the dc link. The indirect ac/dc/ac converter has the same advantages of the matrix converter and demands less unidirectional switches. However, the control of the indirect ac/dc/ac is complex and it is necessary a fairly large three-phase inductance interface in order to reduce the current ripple[4].

Both matrix converter and indirect ac/dc/ac converter demand much more power swtiches and computational effort to implement their control than the traditional voltage source inverter. As a result, those converters are not cost effective.

If the large electrolytic capacitor could be eliminated or replaced by a small nonelectrolytic capacitor, the THD of the input current will be drastically reduced and the reliability of the voltage source converter may increase. On the other side, if the voltage source inverter doesn't have a large energy store element, the dc link voltage will fluctuate with a frequency six times of the supply voltage frequency. Besides this, the ripple on the dc link voltage will increase if the supply voltage is distorted by low order harmonics or unbalance. The dc link voltage ripple causes two problems. The first problem is that in order to have complete control of the synthesized output voltage, the envelope of the output voltage must be fully contained within the continuous envelope of the dc link voltage. This limits the gain of the output voltage to 0,866 of the input voltage regardless the switching strategies. Operation in the overmodulation range is possible [5] but the harmonic components of the input and output current will increase. The same voltage ratio limitation is present at matrix converters and indirect ac/dc/ac converters. The other problem is the production of undesirable low order harmonics in the load side.

To achieve high quality output currents, it is necessary to compensate the dc link voltage fluctuation. A simple current controller based on the calculation of the magnitude of the load currents is proposed in this paper. The modulation index in the space vector modulation is dynamic changed in order to get balanced output voltages with the maximum gain (0,866). Also, this paper presents some design aspects of the prototype inverter and experimental results.

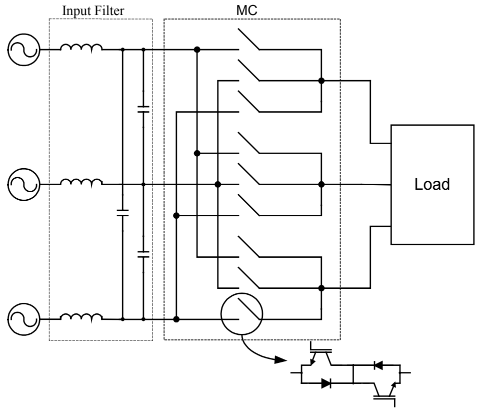

Fig. 1. Matrix converter.

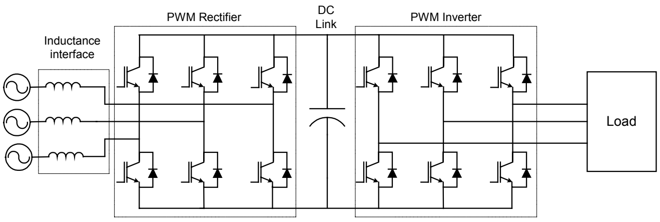

Fig. 2. Indirect ac/dc/ac converter

II. THE PROPOSED CURRENT CONTROL

The space vector modulation (SVM) has been chosen for control of the voltage source converter since the mid-1980s. The advantage of using SVM is the simplicity to perform the switching duty cycle calculation. The duty cycles d_a, d_b and d_0 can be obtained from the following set of equations:

$$\begin{aligned} d_a &= m\sin\left(60^0 - \theta\right) \\ d_b &= m\sin\left(\theta\right) \\ d_0 &= 1 - d_a - d_b \end{aligned} \tag{1}$$

Where m is the modulation index and θ is the angle of the desired output voltage space vector inside a sector.

In order to avoid the influence of dc link voltage variation over the load, the duty cycles must be adjusted as needed. From (1), there is two control parameters that provide a way to modify the duty cycles: the angle θ and the modulation index m. Since the angle θ controls the output voltage frequency, it can be obtained by simple integration of the desired output frequency. On the other side, the modulation index is related with the magnitude of the output voltage. In other words, the modulation index allows performing the compensation of the dc link voltage.

A simple way to adjust the duty cycles is to measure the dc link voltage and use this information to calculate the modulation index *m* at every sample time according to (2). This approach has been presented in [8] but it was first presented in [9] and it was also applied in matrix converters in [10].

$$m = \frac{V_{ref}}{V_{dc}} \tag{2}$$

Where V_{ref} is the magnitude of the desired output voltage.

Another possible way to modify the modulation index is to make use of the load current information. Usually, for high performance applications such as AC motor drives, a frequency converter operating with controlled current is adequate due to the fast response and overcurrent protection. Many types of current control for frequency converter can be found in the literature [6]. Two kind of current controllers are extensively used due to its simplicity: *hysteresis* controller and *ramp comparison* controller. The hysteresis controller, which keeps the error within a specified band, presents good accuracy and robustness. Its major drawback is the resultant variable switching frequency of the converter. In the ramp comparison controller the instantaneous current error is fed to a proportional-integral (PI) regulator that generates the voltage command. This voltage command is then compared to a triangular carrier at the desirable switching frequency. The drawbacks of this controller are that the amplitude of the voltage command should never exceed the triangle slope and the PI controllers do not produce zero current error at sinusoidal condition. Additional problems may arise from multiple crossing of triangular boundaries. The performance of the ramp comparison can be improved if the controller is adapted to a scheme based on the rotating reference frame (dq0 transform).

A simple current control proposed in [7] for a matrix converter is used in this work and it is shown in Fig. 3. In this current control, the measured output currents of the voltage source inverter are used to calculate the magnitude of the output current space vector $\mathbf{I_o}$ according to (3). If the output currents are sinusoidal and balanced, the magnitude of $\mathbf{I_0}$ will be constant.

$$\left|\mathbf{I_o}\right| = \sqrt{\frac{2}{3}\left[i_{oa}^2\left(t\right) + i_{ob}^2\left(t\right) + i_{oc}^2\left(t\right)\right]} \tag{3}$$

Where $i_{oa}(t)$ and $i_{ob}(t)$ are the measured output currents and $i_{oc}(t)$ is the sum of $i_{oa}(t)$ and $i_{ob}(t)$.

On the other hand, if the output currents are distorted by low order harmonics from the dc link voltage fluctuation, the magnitude of $\mathbf{I_0}$ will not be constant. This can be visualized using a particular case where it is supposed that the input voltages are unbalanced so that the output currents are given by following set of equations:

$$\begin{aligned} i_{o1}(t) &= I_p\sin\left(\omega t + \phi_p\right) + I_n\sin\left(\omega t + \phi_n\right) + I_h\sin\left(h\omega t + \phi_h\right) \\ i_{o2}(t) &= I_p\sin\left(\omega t + \phi_p - 2\pi/3\right) + I_n\sin\left(\omega t + \phi_n + 2\pi/3\right) + I_h\sin\left(h\omega t + \phi_h - 2\pi/3\right) \\ i_{o3}(t) &= I_p\sin\left(\omega t + \phi_p + 2\pi/3\right) + I_n\sin\left(\omega t + \phi_n - 2\pi/3\right) + I_h\sin\left(h\omega t + \phi_h + 2\pi/3\right) \end{aligned} \tag{4}$$

Where the subscripts: *p* corresponds to the positive sequence component, *n* corresponds to the negative sequence component and *h* corresponds to the harmonic component. Using (3), after some algebraic calculation, the magnitude of $\mathbf{I_0}$ is given by (5), where it is shown that the magnitude of $\mathbf{I_0}$ is not constant.

$$\left|\mathbf{I_o}\right| = \sqrt{I_p^2 + I_n^2 + I_h^2 - 2I_pI_n\cos\left(2\omega t\right) + 2I_pI_h\cos\left[\left(h-1\right)\omega t\right] - 2I_nI_h\cos\left[\left(h+1\right)\omega t\right]} \tag{5}$$

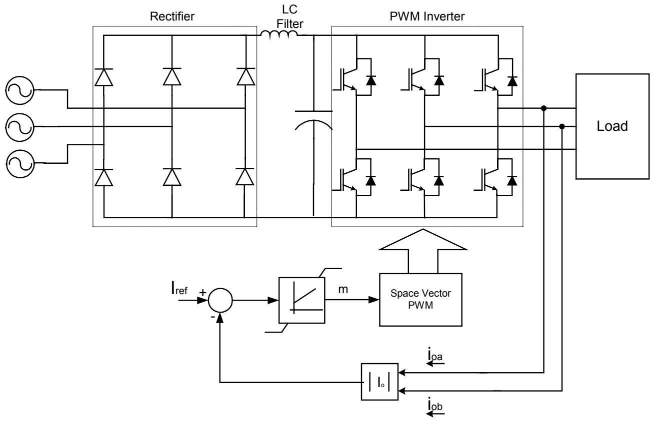

Fig. 3. Proposed controller.

Therefore, the information from the magnitude of $\mathbf{I_0}$ can be used in a closed-loop control in order to modify the modulation index. The magnitude of $\mathbf{I_0}$ is compared with the magnitude of the reference current I_{ref}. Then, the instantaneous magnitude error feeds a PI controller. The output of the PI controller is the modulation index m for the space vector modulator in an effort to keep the magnitude of the space vector $\mathbf{I_o}$ constant.

The control algorithm is given by

$$m = sat_0^{0.866}\left[k_p\left(I_{ref} - |I_o|\right) + k_i \int\left(I_{ref} - |I_o|\right)dt\right] \quad (6)$$

Where: k_p is the proportional gain and k_i is the integral gain.

The tuning of the parameters k_p and k_i of the PI controller is carried out according to the algorithm proposed in [11].

A disadvantage of this current control loop is the controller tuning. If the tuning of PI is not done adequately, the bandwidth of the closed-loop current control may be not enough to get a good compensation. The overall performance of the proposed controller can be improved if a feed forward voltage control using the dc link voltage is added to the current control in order to obtain a lower distorted output current.

III. PROTOTYPE IMPLEMENTATION

At this time two low power voltage source inverters prototypes has been built using the same control circuitry and power switches as shown in Fig. 4. One prototype is a traditional inverter with a bank of 6 electrolytic capacitors giving 1500μF. The other prototype is the inverter with the bank of electrolytic capacitors replaced by a LC filter in dc link to remove the high order harmonics generated by the switching of the inverter [12]. Both capacitance and inductance are small values.

The motivations to build these prototypes are to compare costs and performance. Some design aspects of the prototype are shown in following.

A. LC filter design

The LC filter can be modeled using the harmonic equivalent circuit in Fig. 5.

The damping ratio ξ and the natural angular frequency ω_n are given by

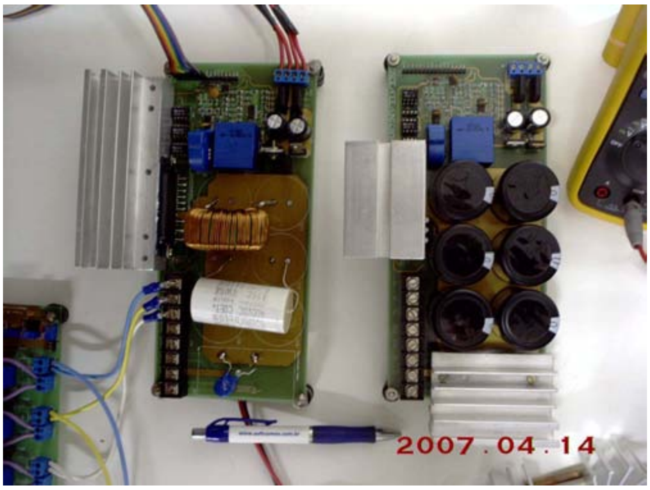

Fig. 4. The inverter prototypes: with LC filter (left), with a bank of electrolytic capacitors (right).

$$\xi = \frac{R_d}{2\omega_n L} = \frac{R_d}{2}\sqrt{\frac{C}{L}} \quad (7)$$

$$\omega_n = \frac{1}{\sqrt{LC}} \quad (8)$$

Where R_d is the damping resistor value.

In the built prototype, the LC filter components are a toroidal inductor of iron powder core with 250μH inductance, a polypropylene-film capacitor with 5μF and a damping resistor R_d with 5Ω. These components lead to a cut-off frequency of 2.9kHz and damping ratio ξ=0.28. The cost of the LC filter was about one sixth of the electrolytic capacitor bank and occupies less space. Moreover, film capacitor is more stable and reliable than electrolytic capacitors in the long term.

Another advantage in replacing the bank of capacitors by a LC filter is that the precharge circuit to protect the voltage source inverter from current inrush during the power up or a line loss event is unnecessary.

B. Protection circuits

Over-current sense signal is obtained from two standard comparators circuit that feed a built-in protection circuit in the IRAMS10UP60A integrated power module [13]. Occurring a short-circuit fault, all IGBTs are disabled. A problem arises when the short-circuit protection is activated: since the load usually is inductive, an overvoltage will appear in the dc link and there isn't a large capacitor to absorb it. This overvoltage can destroy the power semiconductors. In order to avoid this overvoltage, a clamp circuit using varistor is added in the dc link. Varistors can respond to changes in voltage almost instantaneously. Two parameters are important in the selection of the varistor: maximum clamp voltage and the absorb energy capability. In the case of a RL load, the stored energy E is given by

$$E = \frac{3}{4}LI^2 \quad (9)$$

Where I is the rms load current.

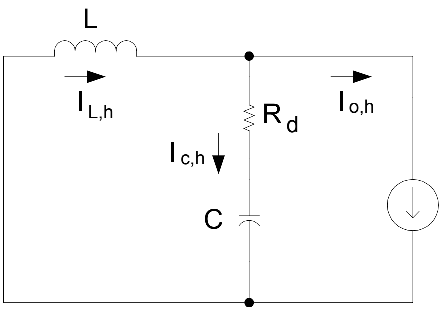

Fig. 5. LC filter model.

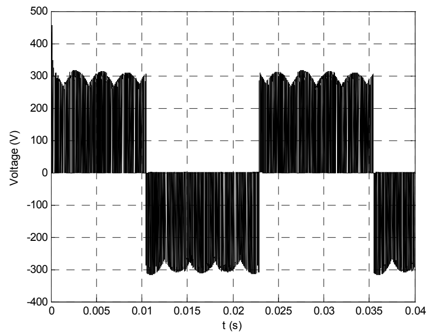

Fig. 6. Output voltage.

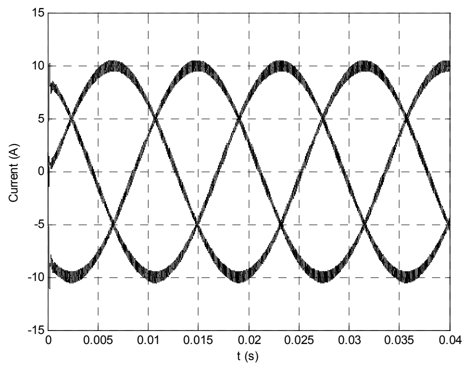

Fig. 7. Output currents.

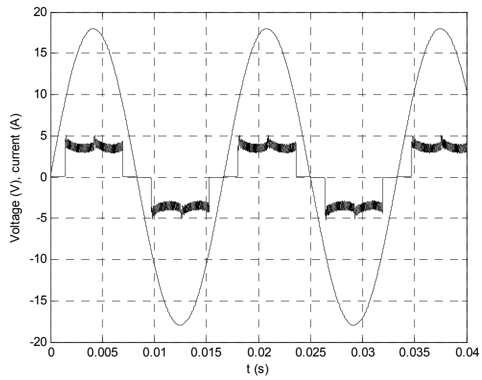

Fig. 8. Input voltage (x0.1) and input current.

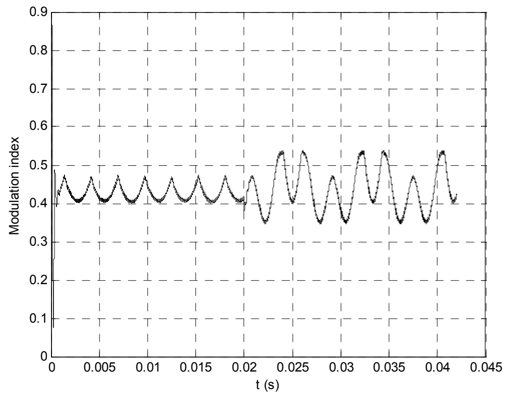

Fig. 9. Modulation index.

C. Limitation of the prototype

For a RL load, the built prototypes were enough to get some experimental results. However, the most common form of load is a three-phase ac motor, which it may be submitted to mechanical or to electrical braking for speed reduction. In either case, the voltage source inverter has to handle the generated power by the kinetic energy stored in the motor and load.

If the load inertia is small or the deceleration time is not so fast, in a voltage source with a large capacitor in dc link, it is possible that the capacitor absorbs the generated power without a significant rise of the dc link voltage. Otherwise, it is necessary a dynamic or regenerative braking circuit in the voltage source inverter. The braking circuit is essential in the case where the voltage source inverter operates without a large electrolytic capacitor.

Another important feature to be investigated and implemented is concern to the ride-through capability [14] of the voltage source inverter without a large electrolytic capacitor since in some industrial applications it is desirable to maintain some degree of control of the process during a momentary power interruption.

IV. SOME SIMULATION AND EXPERIMENTAL RESULTS

The simulation was done using Simulink using the control algorithm given by (6). The filter components are the same used in the prototype. The three-phase load is a Y-connected RL load with R= 10 Ω and L= 6 mH. The switching frequency of inverter is 10 kHz and the input line voltage is 220 V, 60 Hz. Figures 6 to 8 show the performance of the inverter when the input voltages don't present any distortion. The THD of the simulated input current is about 30%. Figure 9 shows the modulation index *m* when the input voltage is distorted at 20 ms after beginning of the simulation with 10% of negative sequence component and 10% of 5th harmonic component. The modulation index is dynamically corrected so that the output currents are sinusoidal and balanced. The simulated transient response of the controller is shown in Fig. 10 when a step change in the reference current is applied. Some experimental results are shown in figures 11 to 15, which figures 11 and 12 are concerned to the voltage source inverter with the electrolytic capacitor bank operating in open-loop and Fig 13 to 15 are concerned to the voltage source inverter without the electrolytic capacitor bank operating in closed loop. The load parameters and switching frequency are the same of the simulations.

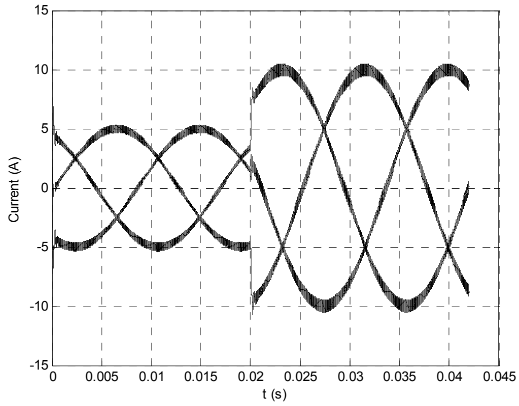

Fig. 10. Output current.

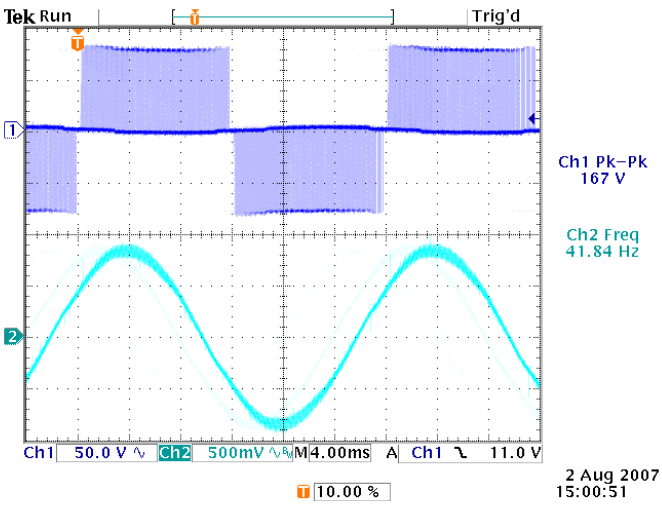

Fig. 11. Output voltage and output current (2A/div) for a voltage source inverter with a capacitor bank.

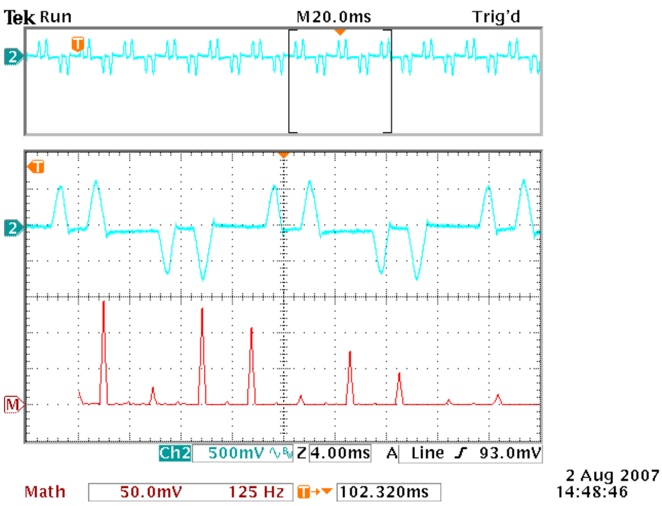

Fig. 12. Input current (2A/div) for a voltage source inverter with a capacitor bank.

Comparing Fig. 12 and Fig. 15 it can be seen that there was a drastic reduction of the input current harmonics when the electrolytic capacitor bank was replaced by the LC filter. The output current quality shown in Fig. 13 is not so good as in Fig. 11. The main reason is the difficulty of tuning the PI

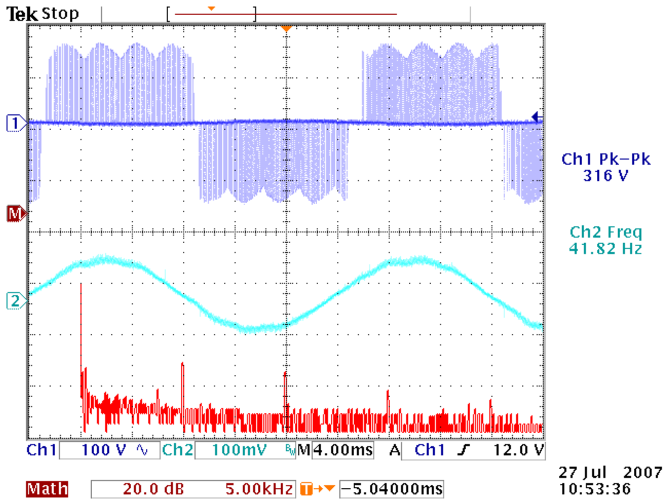

Fig. 13. Output voltage and output current (2A/div) for a voltage source inverter without the capacitor bank.

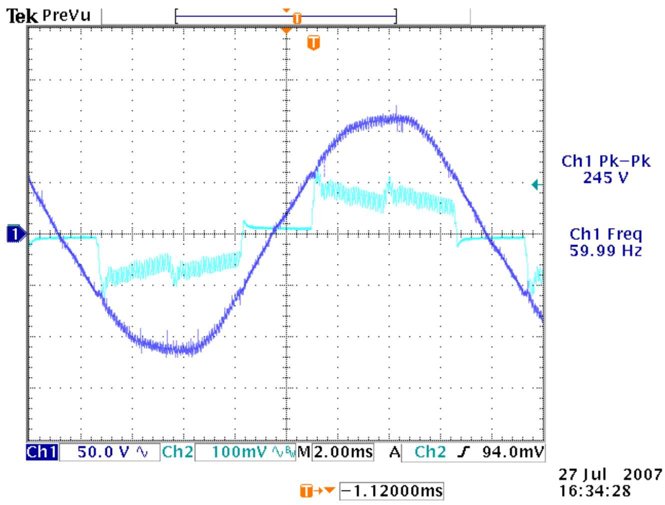

Fig. 14. Input voltage (Ch1) and input current (Ch2 – 2A/div) for a voltage source inverter without the capacitor bank.

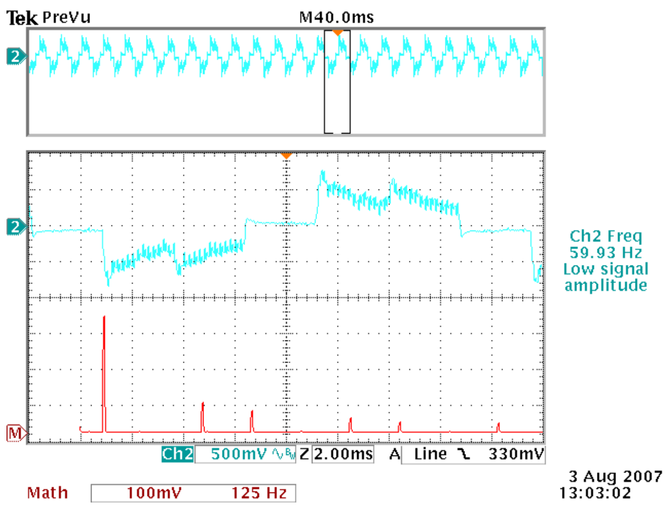

Fig. 15. Detail of the input current (2A/div).

controller due to the inaccuracy of the output currents measurements and others non-idealities present in the prototype. However, the differences are not so high.

V. CONCLUSION

This paper proposes a current control for a voltage source inverter that eliminates the need of a large capacitor in dc link. With the proposed control scheme is possible to obtain a low distorted input and output currents. Simulation and experimental results prove the ability of the current control in counteracting the undesired fluctuation of the dc link voltage besides having a good transient response.

ACKNOWLEDGEMENT

The authors are grateful to FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo – for the financial support and Texas Instruments for the DSP donation.

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