ELECTRONIC CONTROL OF A THREE-PHASE INDUCTION GENERATOR DIRECTLY CONNECTED TO A SINGLE-PHASE FEEDER

Ricardo Quadros Machado[1], José Antenor Pomilio[1], Simone Buso[2] and Fernando Pinhabel Marafão[1]

[1]School of Electrical and computer Engineering – FEEC
State University of Campinas – UNICAMP
Postal Box 6101
13081-970 Campinas - SP
Brazil
(ricardom,antenor,fmarafao)@dsce.fee.unicamp.br

[2]Department of Information Engineering - DEI
University of Padova
Via Gradenigo 6/B
35131 Padova
Italy
simone.buso@dei.unipd.it

Abstract – This paper presents a solution for the direct connection of a three-phase induction generator to a single-phase feeder. This high power quality system is intended to be used in micro-hydro power plants, without control of the turbine. The generated power that is not consumed by the local load is sent to the single-phase feeder. The power flux control is provided by a three-phase PWM inverter, which guarantees the local power quality and controls the power flow through the single-phase feeder. This converter allows balancing the induction generator currents, voltages and frequency. The paper describes the inverter control strategy and presents simulations and experimental results.

KEYWORDS

Induction generator, single-phase feeder, digital control.

I. INTRODUCTION

The advantages of the three-phase induction machine have encouraged significant efforts in seeking approaches to overcome the Induction Generator (IG) poor voltage regulation and frequency variation [1-4]. Some advantages of the induction machines are its robustness, simple construction, little maintenance requirements, wide availability, low cost, and higher power-weight ratio than other electrical machines.

Customers in rural areas, that usually have a single-phase feeder, may request three-phase from the utility and find that it is uneconomical to meet a relatively small three-phase need [5]. On the other hand, there might be energy sources available in some of these areas to produce electric power. For this situation, some authors have proposed the direct connection of the induction generator to the single-phase feeder to obtain three-phase balanced voltages [6-9]. Some of these alternatives operate only under strict conditions and are affected by the AC load variations because are based on the 'Steinmetz' connection. An alternative technique is based on the current's control [9] that is not able to guarantee the AC voltage controllability.

II. THE PROPOSED SYSTEM

The proposed system comprises an IG directly connected to the single-phase feeder where an AC capacitor bank (C_{AC}) provides the IG magnetization.

As the direct connection of an IG to the single-phase utility feeder causes strongly unbalanced voltages and currents at the IG terminals, a three-phase inverter is connected to balance the IG voltages and, as a consequence, its currents (Fig. 1).

The inductors (L_{conv}) are used to do the connection between the inverter and the Point of the Common Coupling (PCC).

The association between L_{conv} and C_{AC} provides the necessary low frequency filtering and the resulting AC voltage is, in practice, free from switching noise.

One important feature of the proposed system is that it does not comprise any speed-governor for the IG, so the generated power depends on the prime-mover power availability. All the power-flux control is based on the local load demand. If the local load demand is lower than the generated power, the excess is sent to the grid. Otherwise, it is possible to absorb additional power from the electric system. If the feeder is not connected, some strategy must be adopted to consume the excess of power, or to reduce the generated power. It is also necessary to guarantee the synchronism before reconnecting the feeder when it is energized.

As the inverter does not manage real power, it is not necessary to have a DC source in the DC link.

III. CONTROL STRATEGY

The control strategy imposes sinusoidal symmetric and balanced voltages on the AC bus. The control of these voltages provides the local load reactive power compensation, assuring that the IG will continue to run normally without losing its magnetization. In addition, the load current harmonics can be partially compensated, but the effectiveness depends on the inverter output impedance compared with the other system impedances (AC capacitors, IG and single-phase feeder impedances). Additionally, the current through the single-phase feeder must have unity power factor (PF). The connection with such feeder is made with an inductor (L_S). In order to control the power flow it is necessary to adjust the local AC voltage amplitude and phase. If the vectors $\mathbf{I}_{source}$ and $\mathbf{V}_{source}$ have the same direction the system is in generation mode. However, if they have opposite directions the system is in co-generation mode, as shown in Fig. 2.

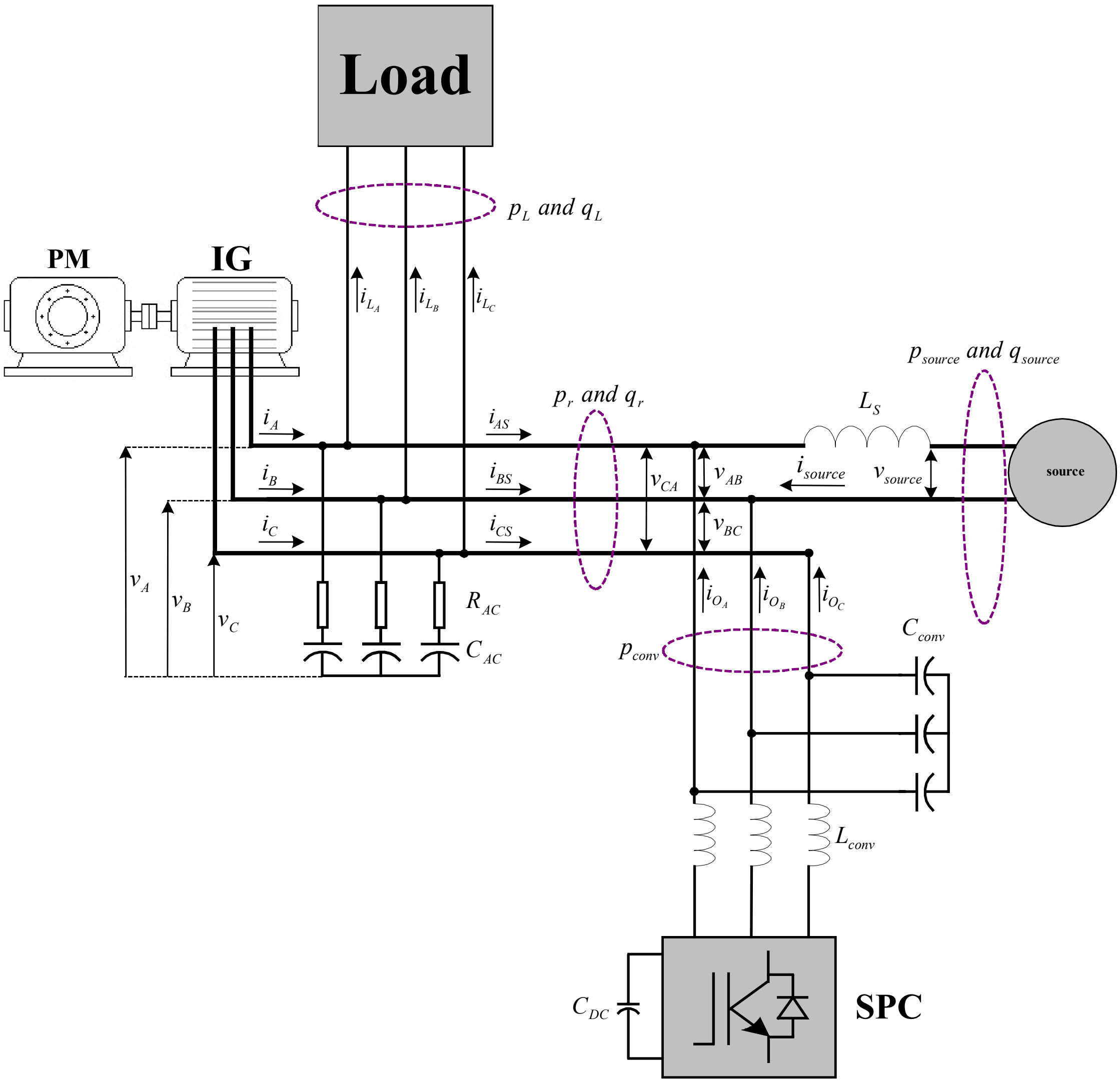
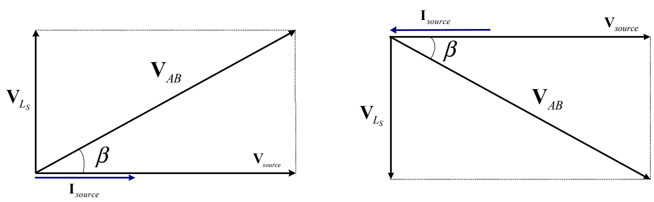


Fig. 1 - System with three-phase inverter.



Generation Mode

Co-generation Mode

Fig. 2 - Phasorial diagrams.

To determine the angle β it is necessary to know the difference between the generated and the locally consumed power (P_r), the connection reactance (X_{L_S}) and to measure the voltage at the source, ($\mathbf{V}_{source}$).

$$\beta = arc\tan\left(\frac{P_r X_{L_S}}{\mathbf{V}_{source}{}^2}\right) \tag{1}$$

The line voltage $\mathbf{V}_{AB}$ is calculated in order to guarantee unity power factor. Obviously, any variation on this voltage affects P_r. Otherwise, designing the coupling inductor for a small voltage drop, the variation in the line voltage can be very small and thus a simple procedure can be adopted.

$$\mathbf{V}_{AB} = \frac{\mathbf{V}_{source}}{\cos\beta} \tag{2}$$

The inductance value can be determined considering the rated power, the PCC voltage range [10,11] and the voltage regulation desired for the local load, setting the maximum β angle for such situation:

$$L_S = \frac{\tan(\beta)\mathbf{V}_{source}{}^2}{\omega_i P_r} \tag{3}$$

Fig. 3 shows the inductance value for unity power factor, considering the variation of the PCC voltage, for different power levels. The selected inductance must be the minimum one for a given power.

IV. SIMULATION RESULTS

The whole system was simulated to verify the effectiveness of the control strategy, analyzing its ability in balancing the IG operation and in controlling the power flux to the single-phase feeder.

A. Non load System

The following waveforms show the uncompensated system, with unbalanced voltages and currents (Fig. 4) and the balanced operation when the inverter imposes the AC voltage allowing the desired grid current (Fig. 5). In both cases all the generated power is injected into the feeder but, in the first situation, the power factor is not unity and the AC voltages and currents are unbalanced. In the second situation, the inverter is able to balance voltages and, consequently, the IG currents. Regarding the grid current, the power factor is unity.

B System with Single-phase Load

The IG (Fig.6) connects a single-phase linear load between phases A and B, whose rated power is 140% higher than produced power. The single-phase feeder provides the deficit with unity PF.

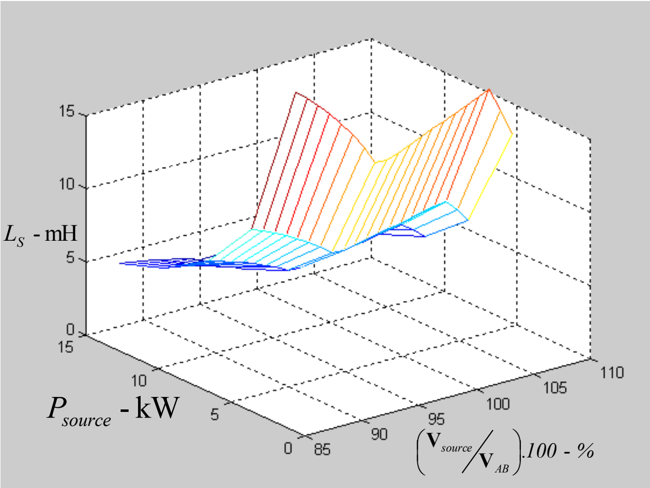


Fig. 3 – Coupling Inductance value L_S for different power levels and PCC voltage.

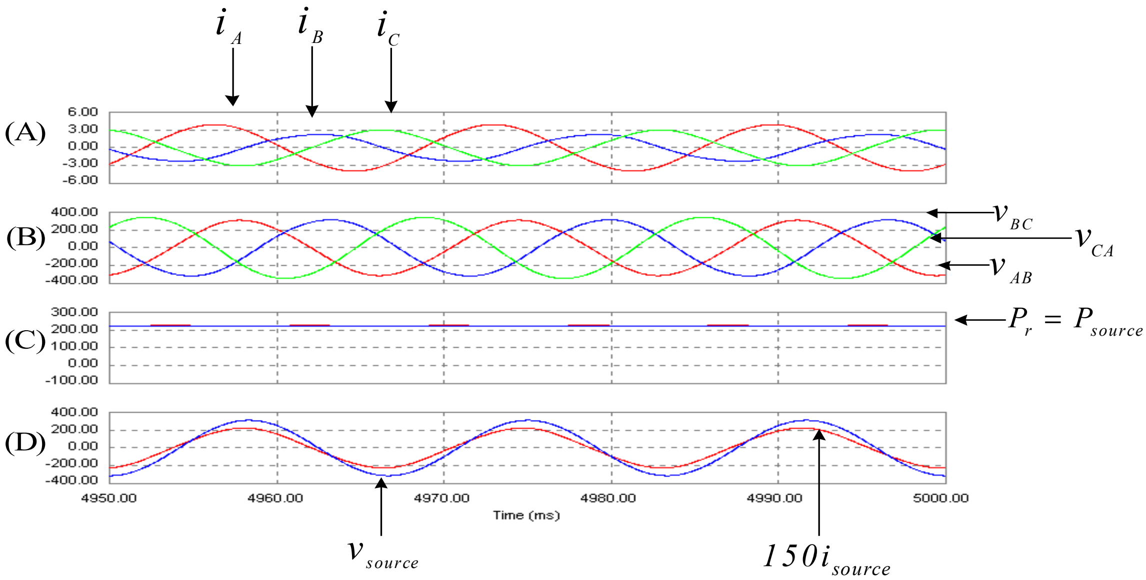


Fig. 4 – No local load uncompensated system.

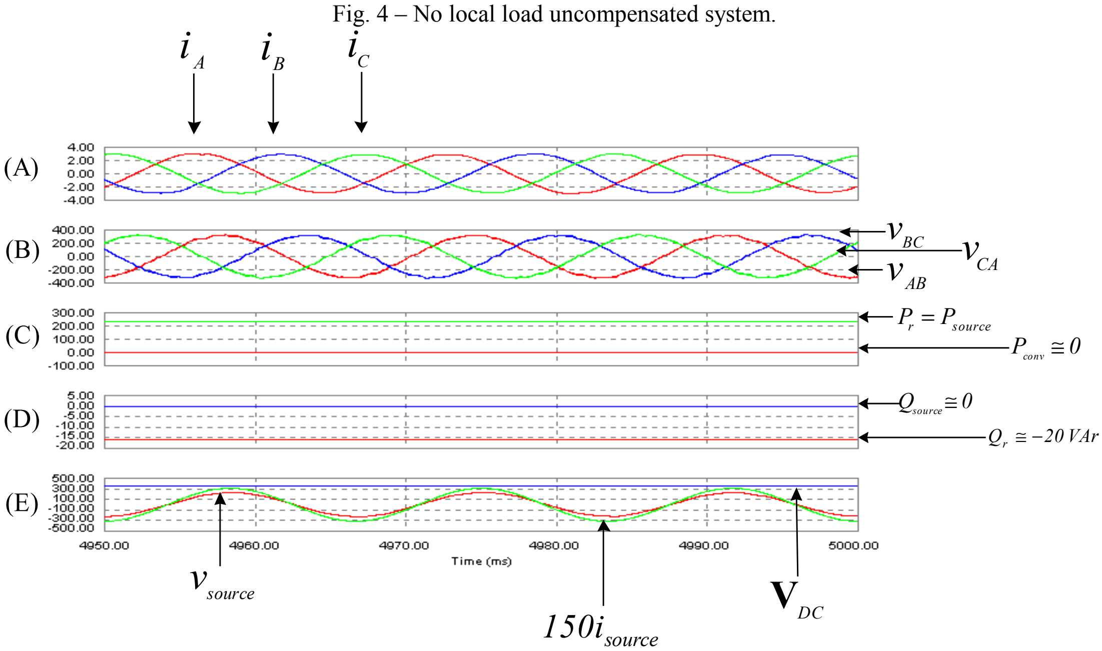


Fig. 5 – No local load compensated system.

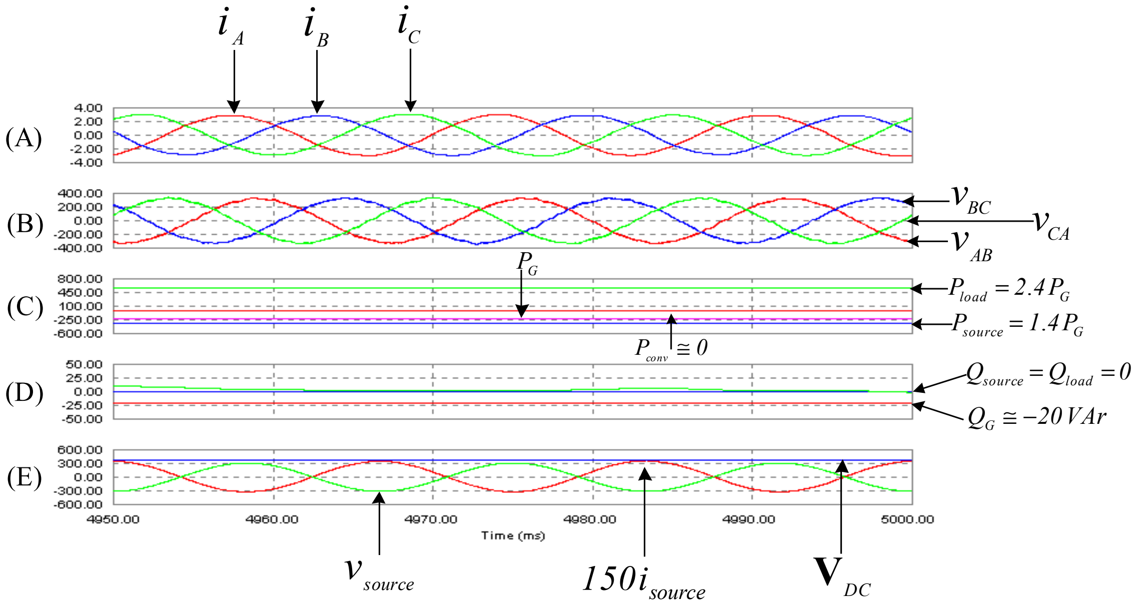


Fig. 6 – Single-phase local load compensated system.

V. OUTPUT CONTROL

To guarantee the inverter voltage quality, closed loop control of the output current and voltage has been implemented. An internal current loop is used to reduce the converter output impedance and improve the dynamic performance, while the external voltage loop guarantees the low error between reference voltage defined in the equations 1 and 2, and the terminal output voltages.

Due the digital implementation and to the need for a reduced switching and sampling frequency (as required by the converter power rating) the voltage controller exhibits a low regulation bandwidth (a few hundred Hertz). To cope with that and provide good control of the output voltage fundamental harmonic component a tuned resonant filter and a feed-forward of the capacitive current are put in parallel to the conventional voltage regulator, so as to boost the loop gain at the fundamental frequency. The feed-forward of the reference voltage is used in the current control to guarantee minimal error between current reference and output current produced by the inverter.

The current and voltage control are implemented in the αβ reference. The k_{cur} and k_{volt} gains represent output to input scale factors while the feed-forward gains *G1* and *G2* are always lower than 1. The SVM block is the gain between Space-vector routine and the output voltage applied by the inverter, always in αβ (Fig.7). $1/sL_{convv}$ and $1/sC_{convv}$ are the transfer function voltage-current and current-voltage respectively (Fig.7).

The DC link control adjusts the β angle based on the DC link active power balance. If the DC link voltage ($\mathbf{V}_{DC}$) voltage is higher than $\mathbf{V}_{DC}$ reference, the DC link has to absorb energy from the system and the β angle should be reduced. On the other hand, if $\mathbf{V}_{DC}$ reference is lower than the voltage reference the DC link has to inject energy in the system and β angle should be increased.

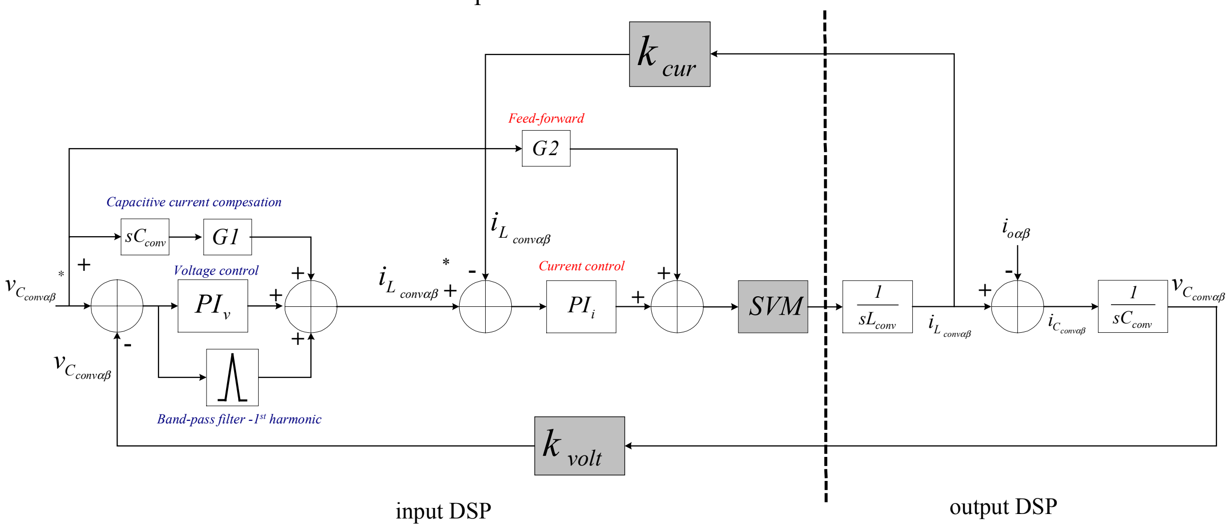


Fig. 7 – Output control.

VI. EXPERIMENTAL RESULTS

The proposed control strategy has been implemented by means of the 16-bit fixed-point DSP-based controller ADMC 401 (Analog Devices). This DSP unit represents a powerful tool for digital control implementation for high-performance industrial applications due to the fast arithmetic unit (38.5 ns cycle and 26 MIPS). Space vector modulation was used to command the switches with 10 kHz as switching and sampling frequency (200 sample for one period). This resolution has 1.8 degrees as error among samples.
The 3 kW experimental setup was built to verify the system operation.

A Static Analyses

In this first situation, the system feeds an unbalanced linear load where P_r is equal to 1800 W.
The Fig. 8 presents the small displacement error and width error between the reference voltage and the voltage applied to IG terminals that were compensated by the DC link voltage control. The PF between $\mathbf{V}_{source}$ and $\mathbf{I}_{source}$ in this case is equal to 0.99 and the THD is 2.2 and 2.28% respectively. The $\mathbf{V}_{AB}$ THD is 0,9%.
In Fig. 9 are presented the three-phase voltages applied by the inverter in the IG terminals. In agreement with what is wanted, such voltages are balanced and their displacement is 120°. Fig. 10 shows a situation in which the load absorbs power from the feeder. The grid voltage leads the output inverter voltage that results in the negative β angle.
The line voltage is filtered to generate the inverter reference. As the load voltage is sinusoidal, the feeder current will be distorted according to the voltage distortion and the coupling inductance reactance.

B Dynamical Analyses

In the Fig. 11 and 12 (zoom of the Fig. 11), a dynamical test was made. A 500 W single-phase load was connected between A and B phases. At the instant that the single-phase load is connected, the $\mathbf{V}_{DC}$ voltage presents a sag, which is suitably corrected by the action of the PI DC-link controller. In principle, the DC link voltage error could be used to adjust either the v_{AB} amplitude or its phase. Adjusting the phase guarantees that the output voltage amplitude is not affected by the load transients.
The small reduction in the width is due to the fact that a larger power should have been absorbed by the feeder (equations 1 and 2).

VII. CONCLUSIONS

This paper proposes a new strategy to compensate unbalanced operation of an induction generator when connected to a single-phase feeder. A PWM inverter generates the voltages necessary to equalize the IG currents.
The control system is implemented using a DSP to sense the necessary input signals and generate the references. By controlling the AC voltage phase and amplitude, it is possible to regulate the power flow through the single-phase feeder. If the locally generated power is higher than the load demand the excess is delivered to the system, otherwise the power deficit is absorbed from the grid. The system guarantees low-distortion, unity displacement factor to the feeder current.

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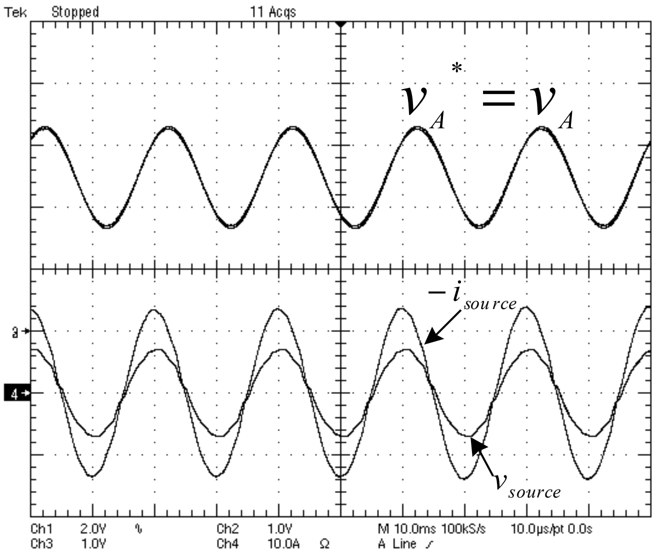

Fig. 8 – Top traces: Filtered grid voltage and inverter voltage (180V/div.). Bottom traces: Grid voltage (360V/div.) and grid current (10A/div.).
Horizontal: 10ms.

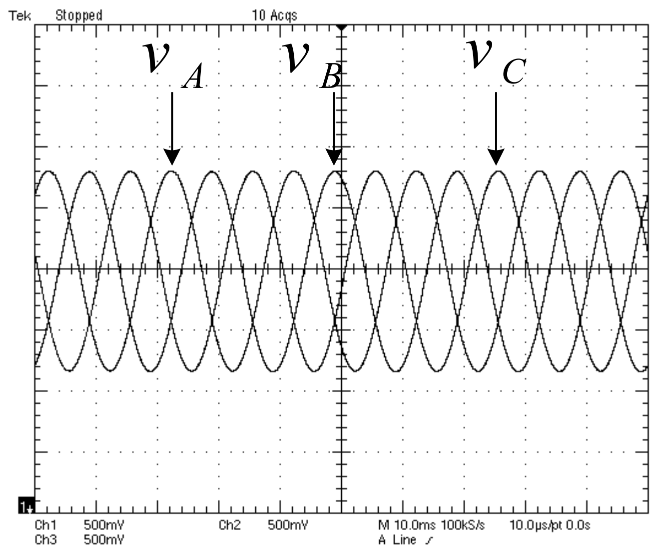

Fig. 9 – Three phase voltages applied to the IG terminals (90V/div).
Horizontal: 10ms.

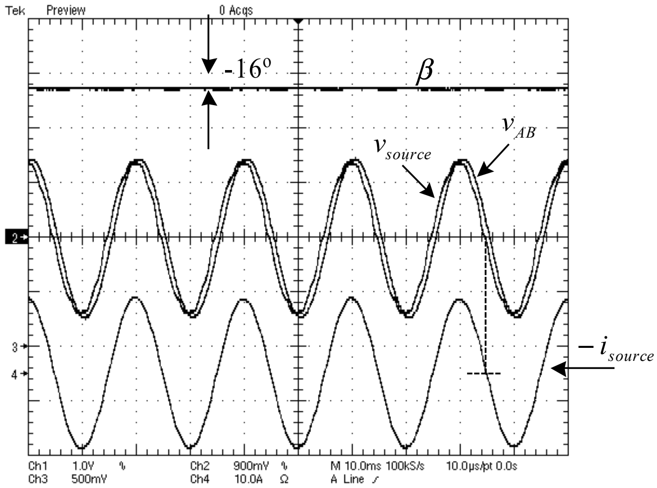

Fig. 10 – Top trace: angle β (500mV = 45°). Middle traces: Filtered grid voltage and inverter voltage (180V/div.). Bottom trace grid current (10A/div.). Horizontal: 40ms.

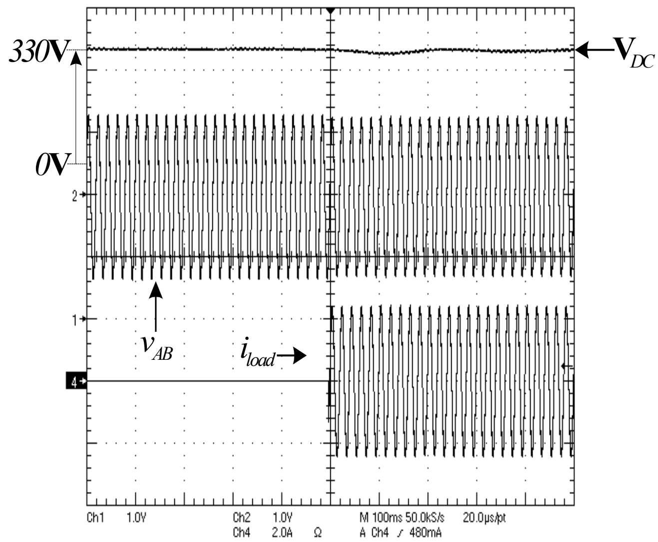

Fig. 11 – Top trace: $\mathbf{V}_{DC}$ (180V/div). Middle traces: Inverter voltage (200V/div.). Bottom trace: load current (2A/div.). Horizontal: 100ms.

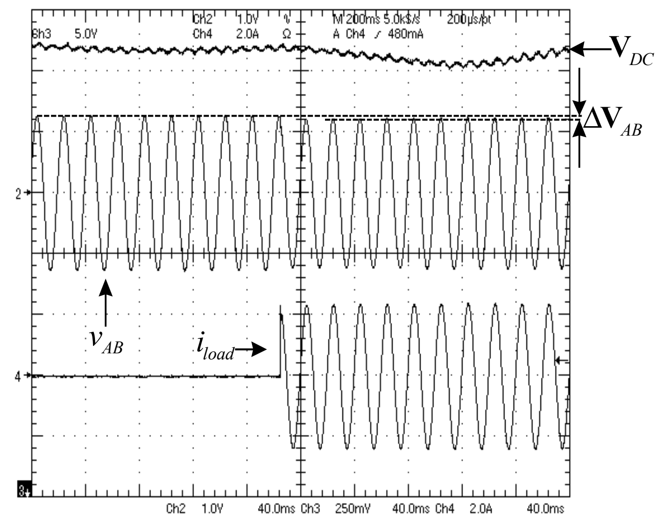

Fig. 12 – Top trace: $\mathbf{V}_{DC}$ (45V/div). Middle traces: Inverter voltage (200V/div.). Bottom trace: load current (2A/div.). Horizontal: 40ms.

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