AC VOLTAGE SUPPLIED BY ALTERNATIVE ENERGY SYSTEM

Andres O. Ortiz, Alexandre M. F. Guimarães, Jossana Ferreira, Filipe O. Quintaes, Armando S. Sanca, Manuel Guilhermino, Vítor L. dos Santos e Victor C. de A. Pimentel
Universidade Federal do Rio Grande do Norte -UFRN- Campus Universitário, s/n, 59072-970- Natal/RN- Brasil
andres@dca.ufrn.br; alexandre@crn.inpe.br; jossana@dca.ufrn.br; filipe@dca.ufrn.br; armando@dca.ufrn.br; guilhermenas@uol.com.br; vsantos@interjato.com.br; vitaumpimentel@gmail.com

***Abstract* – This paper presents the development and implementation of an interfacing system for alternative energy sources and a 1 kW isolated load. The system will be used in the petrochemical industry in applications for extraction of oil in remote places by using positive displacement pumps.**

The system is composed by a step up voltage DC-DC push-pull converter and a full bridge inverter.

The converter amplifies the battery set voltage from 24 V to 350V of an alternative energy system. The duty of the inverter is to deliver energy to the load in the form of a sinusoidal voltage with controlled amplitude, with RMS value of 220 V and low harmonic distortion.

The converter projected uses two PWM (Pulsed Width Modulation) signals generated by a TL494 integrated circuit. The inverter uses a PIC16F877A microcontroller to generate the PWM control.

***Keywords* - Converter, DC-DC push-pull, alternative energy, microcontroller.**

I. INTRODUCTION

Electrical energy generation by means of wind turbines, photovoltaic systems and fuel cells are alternative ways for many demand levels, and it could supply small villages away from the energy network [1-3].

Due to its privileged location, the State of Rio Grande do Norte registers the greatest energetic potential in Brazil as referred to alternative energy sources produced by solar radiation or wind. In the area of Rio Grande do Norte, projects for energy generation using alternative sources are, in general, technically feasible due to the fact that mean solar radiation level by day of the year reaches 20 MJ/m². Also, wind speeds are greater than 8 m/s along the coastal line.

Taking in account these special conditions of alternative energy sources, as well as the opportunities of application presented in the rural areas of Rio Grande do Norte, the aim of this work is to address the question of using solar or wind energy into electrical conventional networks. In this paper, we present the results of a research project which objective was to specify, develop, validate and install an interface system between alternative sources of energy and positive displacement pumps. These pumps are used on oil exploration in artificial lifting systems by progressive cavity pumping. The low cost per installed power compared to systems supplied by electric substations in large distance is the great advantage of the proposed system.

The main technical characteristics of the projected system are: high efficiency (estimated to be greater than 90%); operation power equal to 1 kW; reduced size; on-board electronics; connection with external supervising devices; strength in face of bad climate conditions; and low cost.

II. PUSH-PULL CONVERTER

A push-pull converter is a kind of DC to DC converter that uses a transformer to reduce or elevate voltage, since the relation of transformation is fixed [4].

The main advantage of push-pull converters is its simplicity and high performance in power processing. The input power can be supplied by a voltage or current source; equally, the output power can be delivered as current or voltage. For that, an interface is needed to control the conversion process [5]. The power circuit and the control signal define the converter functional characteristics.

The circuit presented in Figure 1 shows the used topology of DC to DC converter.

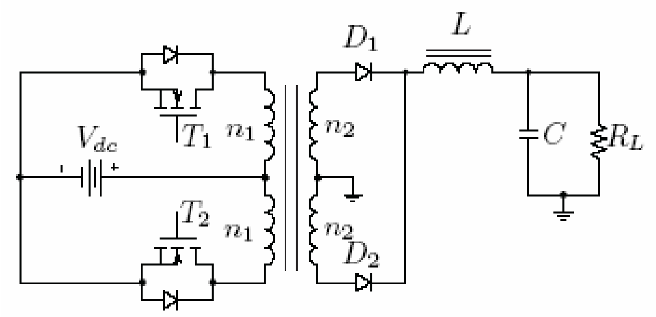

Fig. 1. Push-pull DC-DC Converter

A converter is said to function in continuous mode of current when the summation of current in the switches T1 and T2 results different of zero all over the switching period Ts. In other words, the current in the switches are not equal to zero simultaneously. This means that both the transistor and the diodes are conducting current all over Ts.

In the case that both switches T1 and T2 stop conducting current in any same moment during Ts, then the converter is said to function in a discontinuous mode of current.

To keep the converter in continuous mode we shall choose the worst situation. We will have it when the duty cycle D, that is the relation between the switch active time in the period and the total switching period is minimum.

The converter with the isolator (transformer) is used to isolate the input voltage from the output voltage. The transformer makes this isolation and permits that the relation among turns be used to adjust the maximum and minimum duty cycle into a range of best defined values.

In the push-pull converter the two quadrants of B-H curve are used. It is to say that nucleus magnetization and demagnetization are used to transfer voltage pulses to the inductor [6].

The functioning of the circuit may be described in the following words: when T2 is saturated, T1 must be off and with a tension Vds=2Vdc, due to the phase of primary windings and to the fact that they have the same number n1 of turns. With T2 saturated the input voltage Vdc is applied to one of the primary windings. As the turns relation is N=n1/n2, a voltage pulse is applied to the secondary winding and is rectified by diode D1. It follows that T1 and T2 remain off until T1 goes into saturation.

In the time the transistors are turned off, the two diodes make the secondary to short circuit, once the current of inductor L runs by both diodes at the same time (half of the current to each one, approximately). Then the voltage in the primary of transformer is null and the tension Vds in the transistors equals Vdc. As this dead time is over, T1 comes to saturation and D2 comes to conduct the current from inductor L.

We may note that there are two pulses in a period Ts. To avoid simultaneous conduction by transistors, the duty cycle shall be less than 0.5 [6]. Output voltage may be calculated by the medium value of pulses.

When T1 conducts, D2 conducts too, as shown in Figure 2.

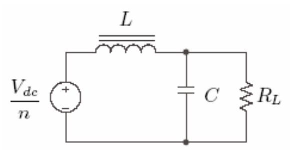

Fig. 2. Converter Circuit for conducting mode of T1-D2 or T2-D1.

Thus:

$$\begin{pmatrix} \frac{V_{dc}}{n} = V_L + V_{RL} \\ V_L = \frac{V_{dc}}{n} - V_{RL} \end{pmatrix}, 0 < t < T_{ON} \quad (1)$$

Where:
V_{dc} is the load voltage;
n is the relation of transformation;
V_L is the inductor voltage;
V_{RL} is the load voltage;
T_{ON} is the key active time in the period;

The Figure 3 shows the moment in which the switches T1 and T2 are not conducting.

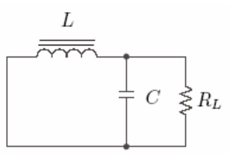

Fig. 3. Converter circuit for not conducting mode of T1 and T2.

Thus:

$$\begin{pmatrix} \frac{V_{dc}}{n} = 0 \\ V_L = -V_{RL} \\ i_{D1} = i_{D2} = \frac{1}{2} i_L \end{pmatrix}, T_{ON} < t < T_{ON+\Delta} \quad (2)$$

Where:

$T_{ON+\Delta}$ is the time;
i_{D1} and i_{D2} are the currents in diodes 1 and 2 respectively.

The process repeats for the other half of period Ts.

$$T_{ON+\Delta} = \frac{1}{2} T_S$$
$$\Delta = \frac{1}{2} T_S - T_{ON} \quad (3)$$

Equaling the above equations we have:

$$\left(\frac{V_{dc}}{n} - V_{RL}\right) T_{ON} = V_{RL} \left(\frac{1}{2} T_S - T_{ON}\right)$$
$$\frac{2T_{ON}}{nT_S} = \frac{V_{RL}}{V_{dc}} \quad (4)$$

If $D = T_{ON}/T_S$, then the output voltage equation is given by::

$$V_{RL} = \frac{2DVdc}{n} \quad (5)$$

The output inductor is selected to limit the ripple current due to the capacitor of the output filter. The Equation (6) is used to calculate the required inductance, L, after that is defined the current's ripple of the inductor, Δ_{iL}. The ripple current of the inductor is equal to 10% of the maximum output current, I_o [7][8].

$$L = \frac{(V_O + V_D) \cdot (1 - D) \cdot T_S}{\Delta_{iL}} \quad (6)$$

Where:

V_O (Output DC-DC converter voltage): 350V;
V_D (Diode Voltage): approximately 1V;
D (Duty cycle): 0.72 for $V_{Imáximo}$=25V;
I_O (Output converter current): 3A;
Δ_{iL} (Ripple peak-to-peak current): (10%.I_O);
Ts (Period): 50μs

Therefore, for L=1490μH. For the project of the inductor it was used the ferrite nucleus NT-23/14/8, from Thorton, with the following characteristics:

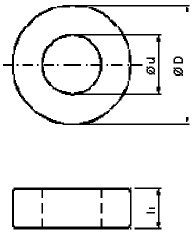

Fig. 4. Dimensões do núcleo NT-23/14/8.

TABLE I
Nucleus Characteristics NT23/14/8 IP6 from THORTON

ΣI/A (mm^{-1})	**Le (mm)**	**Ae (mm^2)**	**A_L (nH)**	**D (mm)**	**d (mm)**	**h (mm)**
1,58	55,8	35,3	1700	**123**	**14**	**8**

From equation 7, we have the number of turns.

$$A_L = \frac{L}{N^2}[nH] \tag{7}$$

Where A_L is the inductance factor [nH], L the inductance [nH] e N the number of turns. From Equation (7), with the values for the parameters already known, the number of turns comes to be 30 [9]. Therefore the inductor designed obtained was 1530µH, close to the required value.

The output filter capacitor can be modeled like a series connection of an inductance, a resistance and a capacitance. The filter must be designed in order to the ripple frequency is maintained in a value lower than the frequency which series inductance value becomes relevant. The series resistance of the capacitor is an important component [10]. To estimate the equivalent ripple value of the series resistance it must assumed that the ripple current of the inductor goes through the capacitor. Thus, the maximum resistance of the equivalent circuit for the capacitor is obtained with the Equation (8).

$$R_s = \frac{V_{ripple}}{\Delta_{iL}}[\Omega] \tag{8}$$

Then, for a ripple peak-to-peak voltage around 0,125V, we will have an inner resistance of approximately 0.04Ω.

For the calculus of the capacitance is used the Equation (9). This is a function of output voltage, inner resistance and the maximum peak-to-peak ripple current. It was specified the aluminum electrolytic capacitor from Siemens with the operation voltage of 350V, capacitance of 3300µF, inner resistance of 30mΩ and ripple current of 9.9A.

$$C = \frac{\Delta_{iL} \times T_{clock}}{8 \times V_o}[F] \tag{9}$$

For the frequency control there is a variation frequency circuit responsible for the managing of the switches [11][12]. It was designed an oscillator circuit using the TL494 from Texas Instruments.

To guarantee the insulation an optocoupler was used as the responsible for the protection of the frequency control circuit as well as to give protection for the user. For the calculus the power levels, the switching time criteria and the insulation level were observed.

For the frequency of 20 kHz there is the need of a time of quick turn off. This is why an interval must be between the rise time and fall time in the waveform of voltage x time graphics, once the fulfillment of this requirement results in an inadequate function of switching [9]. The optocoupler has a high speed detector in which input there is an infrared emitting diode. In the output a receiver Schmitt Trigger delivers hysteresis for noise immunity.

The optocoupler used is H11N1 from Fairchild Semiconductor. The switching and its coupling topology are shown in Figure 5.

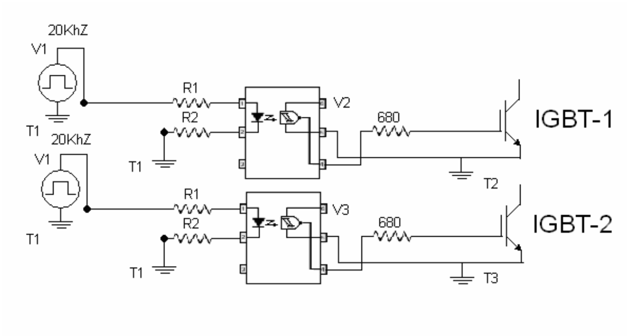

Fig. 5. Switching IGBT's circuit.

The switching devices chosen are IGBT's because they permit an association in parallel to reduce the conduction loses and working with a high switching frequency [7]. The maximum voltage that they support is 60 V. The current depends of the maximum power.

Assuming a performance level of 90%, we know that the output power shall be equal to P = 1000W. Input power then is P_{in} = 1111W. The highest current value occurs when the source voltage is minimum, at 23 V, Ip = P_{in}/ Vdc = 48.3A. As the current divides itself between the two sides equally, the medium current is equal to: Im = Ip/2 = 24.15A. Using a security factor about 20% we have: Im = 30A, and the maximum current Ip = 60A. The same parameters are valid for the freewheeling diodes.

For the rectifiers, we assume a continuous voltage in the filtering capacitors equal to 350 V. The maximal reverse voltage on which diode is: Vp = 2 x 350 V = 700 V. Supposing the existence of losses around 5% in the DC to DC converter, we have the input power in the rectifier block equal to P_{inRET} = 1111 × 0.95 = 1055W; and the medium current is Im_{RET} = P_{intRET}/Vp = 1.507A, plus 20% of security margins Im = 1.2 x 1.507 = 1.809, approximately 2A.

II. TRANSFORMER DESIGN

Due to the high frequency of switching and in order to reduce the losses in the nucleus it was preferred the use of a transformer with ferrite nucleus. The model specified was the NEEL−35/22/15 IP6 without GAP from Thorton Inpec

Eletrônica Ltda, with an inductance factor of A_L = 2000nH ± 25%. Its characteristics are shown in Table II.

TABLE II
NEEL 35/22/15 IP6 nucleus characteristics

∑I/A (mm^{-1})	Le (mm)	Ae (mm^2)	Ve (mm^3)	A_L (nH)
0.90	86.4	95.8	8274.0	2000

By Equation (7) we obtain the relation of transformation $N_{primary}$ = 10 turns and $N_{secondary}$ = 180 turns.

The specifications of the conductor were defined in relation to its current conducting capacity. The option to use many conductors in parallel was taken because it was needed to reduce the skin effect.

III. INVERTER DESIGN

In order to provide the conversion of direct voltage coming from the output of the DC to DC converter to alternated voltage we needed to assemble another converter. This conversion will be made by a DC-AC converter, also called inverter.

The chosen topology for the inverter is presented in the Figure 6. This inverter has a full bridge structure with a filter in the output and it is composed by four switches controlled by the sinusoidal variation of the cyclic ratio. It has a function of generating, following the DC branch, a sinusoidal RMS voltage with value of 220 V and frequency of 60 Hz.

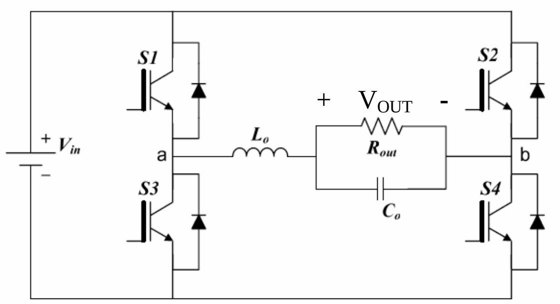

Fig. 6. Full bridge monophase inverter topology

After defining the topology the inverter specifications were calculated. In what follows the requirements for the development of the inverter project are presented.

P_{out} (Output power): 1000W
V_{in} (Input operation voltage): 350V
V_{out} (Controlled output voltage): $220V_{rms}$
f_{out} (Output sinusoidal frequency): 60Hz
THD (Total Harmonic Distortion factor): 5%
Δ_{iL} (Maximum Ripple current of the inductor): $0,5.I_{outpk}$
f_s (Switching frequency): 30kHz
η (Performance estimate): 90%, or greater.

The maximum direct voltage applied over the switches is the output voltage of DC to DC converter, as the maximum reverse voltage over diodes in antiparallel to the used IGBT's.

The peak value of the current that flows through the inductor is given by Equation (10), where its load current I equal to 4,54A.

$$\Delta I_{Lo} = 0,5 \times \sqrt{2} \times I_{out} = 3,21A \qquad (10)$$

The peak level of current in the inductor is calculated through Equation (11).

$$I_{Lopk} = I_{out} + \frac{\Delta I_{Lo}}{2} = 8A \qquad (11)$$

With a modulation rate, m_i, of 0.88 the medium current in the freewheeling diodes is calculated as well as the maximum RMS current of IGBT's. Equations (12) and (13) present these calculations respectively.

$$I_D = I_{outpk} \times \left(\frac{1}{2\pi} - \frac{1}{8} m_i \right) = 0,39A \qquad (12)$$

$$I_{srms} = I_{outpk} \times \left(\frac{1}{8} + \frac{1}{3\pi} m_i \right) = 3,73A \qquad (13)$$

For the calculation of the RMS current of the inductor it is taken in account that the low frequency component (60Hz) is predominant and that it is possible to neglect the effect of waving in high frequency. It follows that in order to determine the RMS value of the winding of the inductor it was taken as equal to the load current, this is: 4.54A.

Based in the limits given to the power components and also in the availability of material we got a specification for the materials to be used. It was adopted the IGBT model IRG4PC50W from International Rectifier and diodes from the same producer model HFA15TB60.

Once the accepted value for the current ripple of the inductor in the output filter is defined, it is possible to determine the inductance and capacitance needed for suppressing the high frequency components of the output voltage of inverter.

The inductance value needed to guarantee the specified ripple is obtained through Equation (14).

$$L_o = \frac{V_{in}}{8 f_s \Delta I_{o\max}} = 454,30\mu H \qquad (14)$$

For the project of the inductor it was used a ferrite nucleus of the model NT-23/14/8 from Thorton, with characteristics already shown in Table I. From Equation (7) it is obtained the number of turns, that is 16.

Following this way, it is possible to specify the output filter capacitor. Equation (15) presents this specification of filter capacitance.

$$C_O = \frac{1}{\left(\frac{4\pi}{12} f_S \right)^2 L_O} = 2,2\mu F \qquad (15)$$

If it is adopted a 3μF capacitor, we can obtain a cut frequency equal to 4.33 kHz, a value also adequate to project requirements.

For controlling frequency there is a frequency variation circuit that is responsible for the switching on. The controlling circuit used presents the microcontroller PIC16F877A, from Microchip, as its main device.

IV. SIMULATION RESULTS

Several simulations were made by using Circuit Maker e o PSPICE to validate and verify the project conditions limits. It was made simulations in opened loop to design the DC-DC converter. A 24VDC voltage with 20kHz switching frequency was used to supply a resistive load.

Figures 7 and 8 show the current e voltage simulations results. It can be showed that current and voltage ripple levels applied to the load are between the specified band.

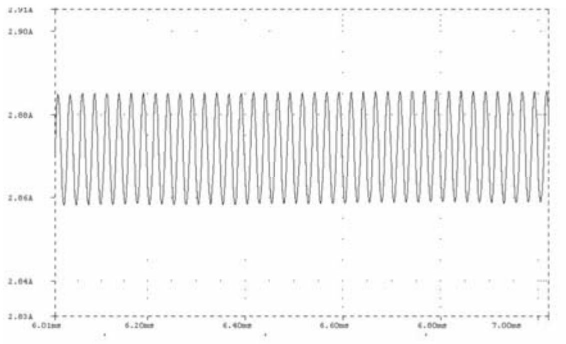

Fig. 7. DC-DC converter output current waveform.

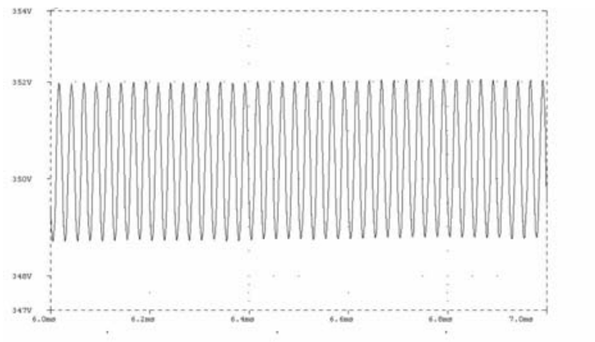

Fig. 8 DC-DC converter output voltage waveform.

The simulation um Figure 9 was made to watch the effort on semiconductors for the highest input voltage condition.

Figure 9 shows the voltage waveform on the DC-DC converter switches. It can be seen a 55VDC peak voltage according to the project.

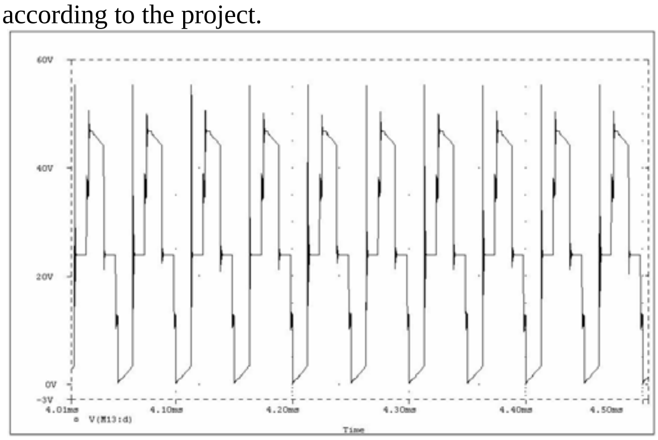

Fig. 9 Forma de onda de tensão sobre as chaves do conversor DC-DC.

The simulation performance was satisfactory. Therefore the project of the converter was adequate too.

The efficiency of the system was calculated from the losses in the stages of DC-DC converter and the inverter, taking into consideration the work conditions of the inductors, switches and transformer. The calculated losses of the system were about 90W.

V. EXPERIMENTAL RESULTS

The designed converter was then simulated by using softwares Circuit Maker and PSPICE. Following this, the DC to DC converter and the inverter were built on a printed circuit board and were made the first empirical tests. In the first part of tests, a resistive load was used and half of the total power projected, that is, 500 watts was applied on it. The results of these tests are presented in the Figures 4 to 8.

Figure 10 presents the output waveform for the two switches of the oscillator circuit for the PWM output generation to the converter. For this oscillator the TL494 from Texas Instruments was used. In this circuit there is a potentiometer for setting the output frequency in 20 kHz.

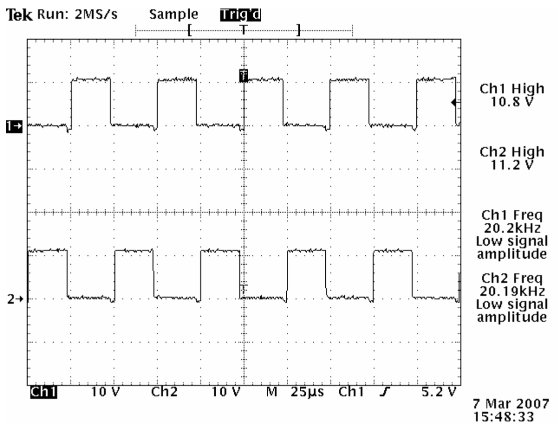

Fig. 10. PWM's oscillator circuit output.

For the transformer isolated tests were executed in order to verify the relation of transformation. A signal generator was used, that has a sinusoidal waveform and a frequency of 20 kHz. Figures 11 and 12 present the primary and secondary waveforms respectively. Results show that the relation of transformation is the same as projected.

Using a DC source we also made tests with the inverter.

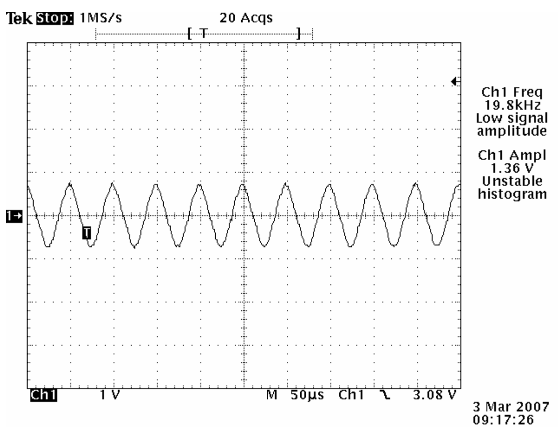

Fig. 11. Transformer primary winding waveform

After testing the transformer alone, a test was made in which a resistive load was coupled to the transformer with the aim of verifying the output converter voltage, that is, the link DC voltage delivered for the inverter branch. This result is presented in Figure 13.

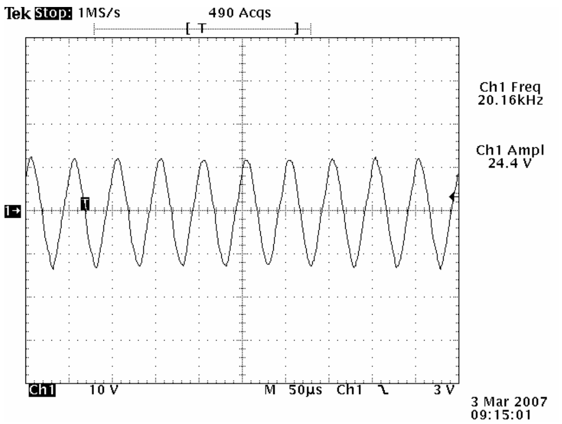

Fig. 12. Secondary Winding Waveform

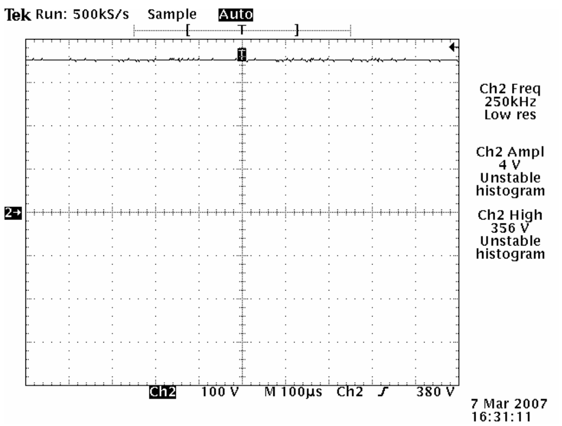

Fig. 13. DC to DC converter output waveform

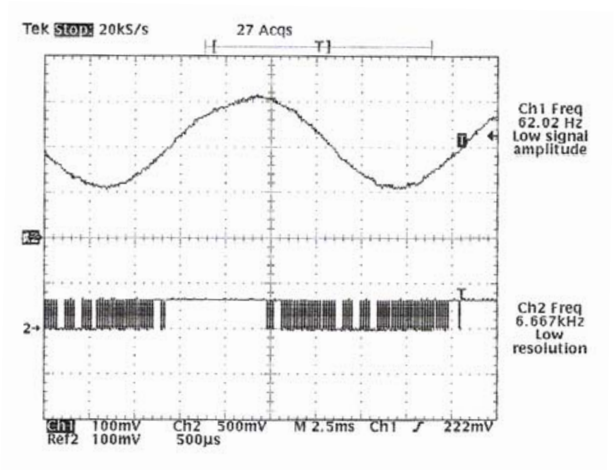

Fig. 14. Output waveform of inverter (Ch1) and PWM output applied on IGBT(Ch2)

Figure 14 presents the PWM output signal of the microcontroller PIC16F877A.

VI. CONCLUSIONS

The interface system for alternative energy sources and conventional electrical network was approved in the tests for supplying power to isolated loads. The experiments made show that the system has a very satisfactory performance.

The total performance presented by the system reached an effectiveness rate around 92%. This result of great performance is linked to one of the most important requirements for this project.

Although the majority of the tests have been made with restriction of the power level, because of limits in the primary winding current of the used transformer – the projected transformer was not available yet – it was possible to certify the good performance of converter.

In the tests executed with the DC to DC converter and the inverter, these worked as we expected.

In lab tests with the DC to DC converter and the inverter, both behave in agreement with the design expectations.

REFERENCES

[1] Prospects for Distributed Electricity Generation. The Congress of the United States, Congressional Budget Office Publication, 2003.

[2] B. Kroposki, R. Deblasio, and J. Galdo, “Distributed Power Program DER Pilot Test at the Nevada Test Site”. National Renewable Energy Laboratory, 2002.

[3] N.R. Friedman, “Distributed Energy Resources Interconnection Systems: Technology Reviews and Research Needs”. National Renewable Energy Laboratory, 2002.

[4] R. W. Erickson, “Fundamentals of Power Electronics”, Chapman & Hall, 1997.

[5] J. Yim, I. Kim, D. Kang and B. Kim “High-efficiency push-pull power amplifier with high operation voltage”. IEEE Microwave and wireless components letters, Volume 17, Issue 5, 2007.

[6] S. Ristic and N. A. F. Jaeger, “Improved push-pull polarization modulation using coupled quantum-well structures”, IEEE Photonics Technology letters, Vol. 19, N.10, 2007.

[7] Wu Jia-ju, H. Sugimoto and Wu Sheng-yu, “Determination and relativity of leakage indutance of push-pull transformers”, IEEE Power Eletronics Specialists Conference, 2006. PESC 2006.

[8] C. W. Lander, “Eletrônica industrial: teoria a aplicações”, São Paulo: McGraw-Hill, 1988.

[9] T. M. U. Mohan and P. R. William, “Power eletronics: converters, applications and design”, John Wiley & Sons. New York. 1989.

[10] M. H. Rashid, “Power eletronics: circuits, devices, and applications”, Prentice-Hall. Englewood Cliffs. New Jersey. 1993.

[11] IEEE Standard 1547-2003. “Standard for Interconnecting Distributed Resources with Electric Power Systems”.

[12] “Application Guide for Distributed Generation Interconnection: 2003 Update The NRECA Guide to IEEE 1547”, Resource Dynamics Corporation, April 2003.