HIGH FREQUENCY CONVERTER BASED ON RESONANT INVERTERS FOR EXCITING A 50KW INDUCTIVE COUPLED PLASMA TORCH

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Abstract **- This article presents the concept, the modeling and the simulation of a high frequency converter based on series resonant load inverters using the sequential gate pulsing method for increase the operating frequency limits. This converter is purposed for the excitation of an inductive coupled thermal plasma torch used in an industrial waste treatment plant. It is constituted by a connected parallel group of four identical 50kW IGBT inverter modules and operates at the nominal frequency of 450kHz. All inverter modules are configured in the full-bridge configuration scheme and use the fastest IGBT devices produced by means of the new NPT technology. In order to reduce the IGBT switching losses, ZVS soft switching techniques are implemented. A DSP module and its associated subcircuits provide the command, the control and all management facilities of the resonant converter. The DSP software is developed in the ANSI C language. A RS232 serial communication interface permits the parameter adjustments of the RF power supply unit required by the operational process of the plasma waste treatment plant. The control process is provided by an external PC microcomputer that communicates with the RS232 interface. This control application is implemented in the LabVIEW® environment running under Windows® platform. Specific simulation tools like the MATLAB® and the Simulink® are also used to model and simulate the system response. Additionally, some simulations in the PSpice® tool were implemented to choose the better inverter topology, evaluate the commercial performance of the specified devices and predict the circuit behavior. The experimental tests are being achieved using a 50kW non-inductive resistive load.**

Keywords **- DSP, IGBT, ICP Torch, NPT Technology, Series Resonant Inverter.**

I. INTRODUCTION

The high frequency series resonant converter proposed and described in this paper is part of a Radio Frequency (RF) power supply purposed to equip an experimental thermal plasma waste treatment plant. To understand the academic context that motivated the development this project it is necessary to remind the recent demands imposed by the Brazilian environmental legislation, the regulatory federal agencies [1] (CONAM, ANVISA, COVISA, etc.) and by other environmental control organizations acting in the state federation and/or municipal ambit. All regulatory legislation forces the industrial and the medical segments to offer an appropriate treatment and a good final destination for the produced residues. The high processing costs and the pratical difficulties to discard the residues engendered by these new environmental demands suggest that it might be considered the commercial values aggregated to the waste. In this treatment plant the inorganic waste components could be recycled and the organic part processed to produce synthesis gas, thermal vapor and/or electric power in a co-generation scheme. The pilot plant placed at the DCA/DFTE/UFRN is currently in implantation phase. This plant intends to prove the potential possibilities of this emerging technology and extend its benefits to new application fields, as well as to offer an experimental laboratory for the development of new converters and other equipments related to this segment.

Like this, the focus given to this paper is willfully descriptive in order to facilitate the understanding of the system overall. The concept details of the high frequency series resonant converter, the main elements design, as well as the control strategies and the switching sequences used for the command of the inverter modules will be presented in this paper.

II. EXPERIMENTAL PLANT DESCRIPTION

The experimental thermal plasma industrial waste treatment plant is essentially constituted by a RF power supply, an inductive plasma torch, a plasma process reactor and its associated auxiliary subsystems. The high frequency series resonant converter described in this paper is part of the RF power supply unit. The Figure 1 shows the illustrative diagram of the waste treatment plant with the RF power supply unit and its several associated subsystems.

The RF power supply unit is built on two solid-state medium power static converters, being one of the AC/DC type and another one of the DC/AC high frequency inverter type. The AC/DC converter is constituted by a three-phase boost rectifier acting as power factor pre-regulator [2] that feed the DC bus system at $750V_{DC}$@75A. The three-phase boost rectifier uses the space vector modulation scheme to synthesize the phase currents and implement the Power Factor Correction (PFC) near the unity in each phase of the utility lines. The DC/AC high frequency series resonant converter operates at the nominal frequency of 450kHz, supplying the sinusoidal current to excite the 50kW RF inductive coupled plasma torch by means of the impedance matching high frequency transformer.

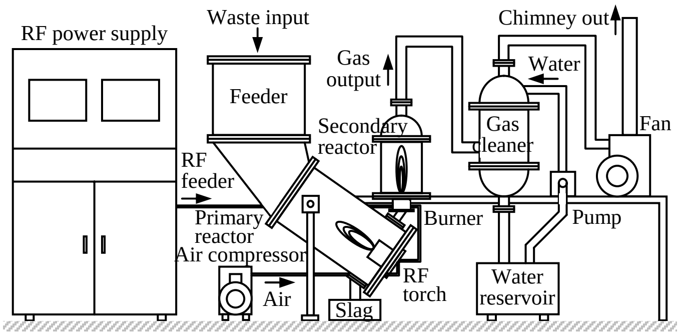

Fig. 1. Illustrative diagram of the plasma waste treatment plant.

The high frequency series resonant converter is built on a set of four 50kW full-bridge series resonant load inverter modules, parallel connected and switched according to a sequential control scheme. A RF power transformer is built on a ferrite core and it is inserted between the converter and the torch in order to provide the impedance matching to the load. Also, it performs galvanic isolation to the utility lines, eliminating electrocution risk to the operator. The full-bridge inverter modules are equipped with fastest Insulated Gate Bipolar Transistor (IGBT) [3] devices using the Non Punch Thru (NPT) technology. This technology offers substantial reduction of the switching losses at high frequencies and they incorporate a fastest reverse free-wheeling diode for the current circulation return. The IGBT modules and the driver modules are mounted on a heat sink constituted by an extruded aluminum block. This block is cooled by a forced-air flow. A TMS320F2812 Digital Signal Processor (DSP) module provides the generation of the IGBT command pulses, implements the control strategy scheme, generates the command sequences for the inverter modules and it processes all the several control signals, as well as load resonance frequency tracking. All the connections between the DSP and the IGBT driver modules are made by fiber optic links, avoiding EMI disturbances possibility in the command lines. The IGBT switching of the full-bridge inverter structures are made by a soft switching scheme using Zero Voltage Switching (ZVS) technique in order to minimize the switching losses and the electrical stress on these devices. The programming of the DSP module is made in the ANSI C language by means of its own programming environment which contains a set of predefined functions.

A $380V_{AC}$/100A tree-phases utility line feeds the RF power supply unit. Both AC/DC and DC/AC converters are physically mounted in two 24 height units by 19” standard racks. The RF power supply unit incorporates also several auxiliary functionalities such as the supervisory system, the internal protection for the high power circuits and the measurement facilities for monitoring the main operational parameters. The modular structure concept adopted in the project and construction of the RF power supply unit will make possible that hereafter new association of inverter modules will be implemented in order to reach the requested power to equip larger capacity plants.

III. HIGH FREQUENCY SERIES RESONANT CONVERTER TOPOLOGY

Four identical 50kW inverters constitute the main part of the high frequency series resonant converter. Each inverter structure is rated to the nominal value of 50kW and uses a dual SEMIKRON SKM100GB125DN ultra-fast IGBT module. A pair of SKHI 26F driver modules excites each resonant inverter module. These IGBT devices are produced with a thin transparent emitter structure obtained by a new technology process and they present typical switching turn-on and turn-off delay times of 80ns and 350ns, respectively, making possible to handle currents in order of 100A under 1200V. These modules incorporate an anti-parallel diodes pair that presents similar recovery time characteristics. The IGBTs switching frequency is closed to the resonant frequency f_0, determined by the series elements of the resonant load. It is constituted by the compensating capacitor C_c, the coil inductance L_c of the plasma torch and the reflected resistance R_L of the plasma. Thus, the load resonant frequency f_0 is determined by:

$$f_0 \cong \frac{1}{2\pi\sqrt{L_c \cdot C_c}} \tag{1}$$

The Figure 2 shows the simplified circuit diagram of the high frequency series resonant converter and its principal connections with the resonant load and the DSP module.

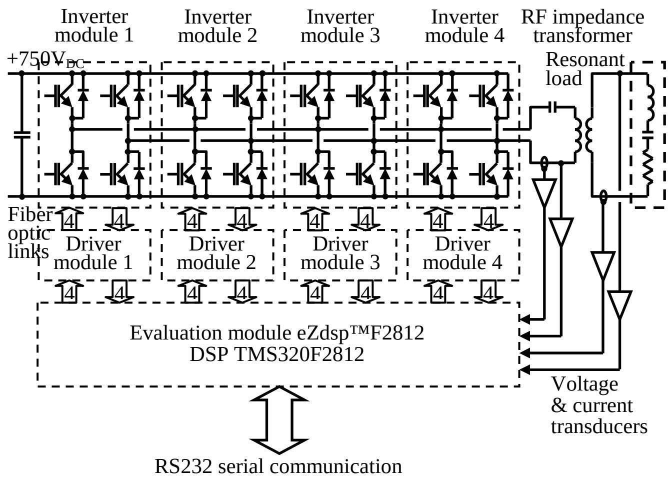

Fig. 2. Simplified circuit diagram of the high frequency series resonant load converter.

In order to reduce the switching losses, two methods could be employed: current derating and/or current destressing. For this case, the method chosen is the destressing current implemented by sequential gate pulsing. It was observed that the IGBT losses to current ratio characteristic present a non-linear behavior and the dominant turn-off losses do not increase linearly with the increasing current. This property is also used and the IGBT devices are operated closed to the nominal current values. Due to this, a simple current derating is far less efficient than a sequential gate pulsing [4]. By this method, a destressing provided by the reduced frequency switching is rather than the current derating. The reduced switching stress allows that the IGBTs operate at much higher current level than if they were switched in each period. The high current operation of the IGBTs secures a most effective turn-off, or more precisely, the minimum turn-off loss to current ratio. One inverter module conducts the full output current, but it is relieved by the currentless periods. The IGBTs switching frequency is lower than the resonant frequency. The number of currentless periods equals the number of inverter modules minus one [5]. The Figure 3 shows the sequential command scheme that was adopted and highlights the ZVS conditions near the zero voltage transition points.

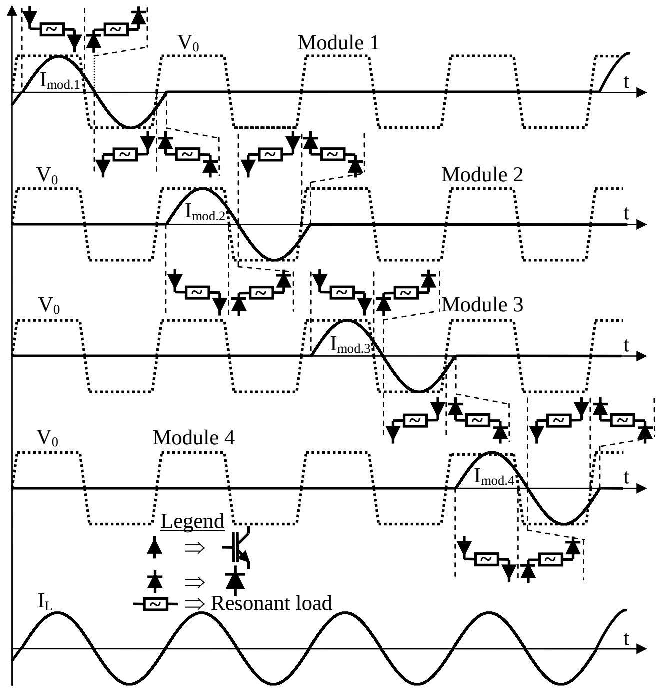

Fig. 3. Simplified diagram of the inverter stages commutation sequence.

In order to preserve the ZVS condition it is necessary to keep the current slightly lead, independently of the load resonance condition. Once the load resonance frequency is imposed by the intrinsic plasma conditions, and it cannot be changed, then it is necessary to keep the inverters frequency switching slightly higher than the load resonance frequency. The Phase Locked Loop (PLL) algorithm implemented on the DSP module tracks the resonant frequency of the load and generates the command signals to the IGBT inverter modules [6]. The signals are transmitted to the IGBT drivers through optic fiber links. Two high frequency current transducers detect the load current zero crossing signal and measure the load current signal value. With the sequential gate pulsing scheme it is necessary to exist a communication between the DSP module and each inverter module in order to pass on the token to the next active cycle. Besides, the DSP module implements the additional functionalities requested by the high frequency series resonant converter such as protection, supervision, status and alarms. A RS232 serial interface allows entering all operational parameters and makes possible the communication with the supervisory unit of the RF power supply.

The full-bridge resonant inverters are designed to constitute a modular system. In order to minimize the parasitic inductances and provide a better space arrangement, the four inverter modules are vertically grouped and distributed around the DC bus, assuring the necessary symmetry to the inverter set. The high frequency transformer is built on a ferrite C core with the primary and secondary windings constituted by plane copper coils. The primary to secondary relationship transformer is made 4:1. The high frequency transformer is cooled by a circulating water flow. The power of the system transmitted to the load is controlled by regulating the DC-link voltage. The output power P_{out} is given by:

$$P_{out} = \frac{2.\sqrt{2}}{\pi} \cdot I_L \cdot V_{DC} = \frac{8}{\pi^2} \cdot \frac{V^2{}_{DC}}{R_L} \tag{2}$$

The P_{out} value corresponds to 1st harmonic current term of the Fourier series once that the waveform of the output voltage V_L applied to the load is square.

IV. DSP-BASED PLL CONTROL SYSTEM

A PLL control algorithm has been developed for the specific purpose [7] and it is implemented by the special hardware feature of the TMS320F2812 DSP module. This DSP module operates at a speed of 150 MIPS, witch makes it possible to control the switching pulse generation system up to 500 kHz. The digital implementation of the PLL function maintains the resonant operation over a wide range of frequencies, from 400 to 500 kHz. We are considering that these values will be enough to track and accommodate the variation impedance produced by the plasma fluctuations on the resonant load. This is an acceptable condition considering that the power control will be made mainly by adjusting the DC link voltage, between $550V_{DC}$ and $750V_{DC}$.

The Figure 4 shows a block diagram of the PLL system.

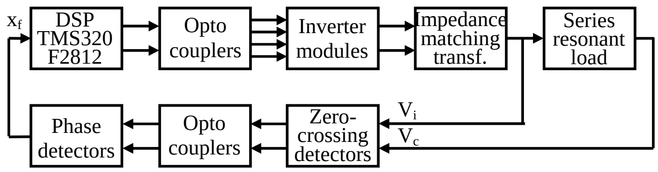

Fig. 4. PLL block diagram.

The compensating capacitor voltage V_C and the inverter output voltage V_i are measured with a set of high frequency voltage transducers using the Rogowsky bobbin principle. These transducers present a negligible sample delay and the zero crossing of these voltages are detected and compared in an XOR gate, as shown in Figure 5a.

The output of the XOR gate is filtered to yield a DC voltage V_f. This DC voltage is proportional to the phase difference between the capacitor and inverter voltages.

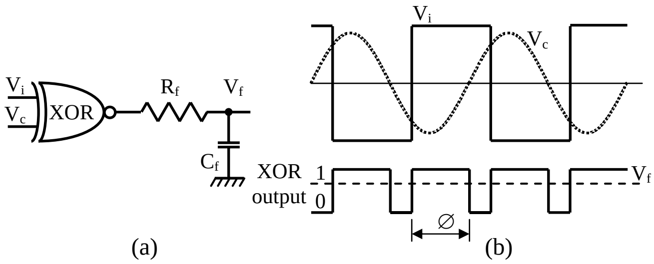

Fig. 5. Phase detector:
a) Phase detector circuit diagram; b) PLL waveforms.

The Figure 5b shows the PLL waveforms. This voltage V_f is isolated by a optic coupler and applied to the analog input of the DSP where digital implementation of the PLL scheme is then realized.

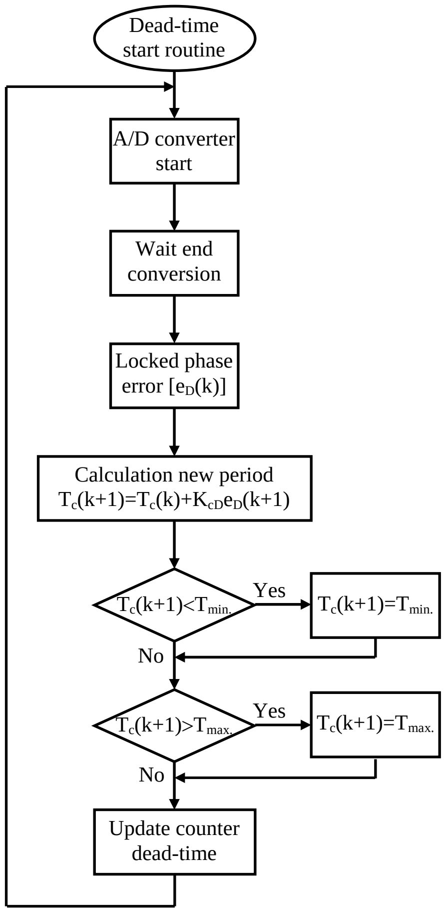

Fig. 6. PLL control algorithm flowchart.

The flowchart of the PLL control algorithm is shown in Figure 6. The voltage input V_f of the DSP, which is proportional to the phase difference between the capacitor and inverter voltages, is compared with a value corresponding to 90 degrees and the switching frequency is adjusted so that this difference is made zero. When this condition is achieved, the capacitor and the inverter voltages are in quadrature, which ensures that the inverter voltage and current are in phase. Hence, the resonant frequency f_0 of the load [8] can be tracked and meanwhile to keep ZVS conditions.

The PWM outputs of the DSP are used to generate the switching pulses for exciting the IGBT inverter modules. The PWM periods determined by the PLL algorithm are loaded into the timer control register, which then starts generation of the PWM switching pulses. The dead-time delay between the switching instants of the IGBTs on the same leg of the inverter [9] is provided by the dead-time control register. This delay is adjusted by the special hardware feature of the DSP and it is independent of the processing delays. It is being fixed in 100ns. This feature of the DSP maintains a constant delay at all frequencies, which is not possible in analog circuit implementation of PLL control due to the variation of components characteristics with frequency and aging drift.

V. SYSTEM MODELING AND SIMULATION

A simulation model has been developed using the Simulink® tool, which has been used to analyze and design the PLL control system. A mathematical model of the PLL control system has also been developed in discrete time, in which the stability of the system can be assessed. For simplification, this model does not simulate the PLL control algorithm as in the actual practical implementation, with the period T as the output of the Voltage Controlled Oscillator (VCO). Instead, the frequency of the VCO in this model is controlled by the VCO input. However, the resulting behaviors from the two approaches are expected to be similar for sufficiently small deviations around the operating point.

The Figure 7 shows the simulation model for a complete system.

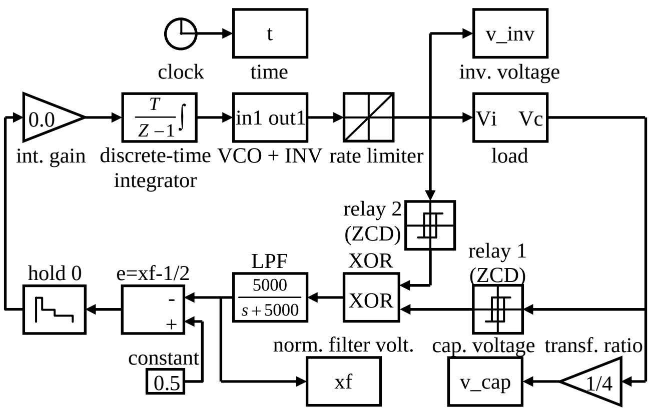

Fig. 7. SIMULINK model for the inverter system.

In the Simulink® model [10] used for modeling the system, the compensating capacitor C_L and the inverter voltages V_i are passed through relays which represent Zero-

Crossing Detectors (ZCD) which the output are applied to the input of the XOR. The Low-Pass Filter (LPF) output is compared with the reference value and the error is sampled by a first-order sample-and-hold which represents the analog-to-digital conversion operation. The discrete time integrator implements the integral controller. The VCO output in this simulation is the square wave inverter output voltage applied to resonant load.

Figure 8 shows the simulation results for the steady-state operation of the inverter system. V_i is the inverter output voltage and V_C the compensating capacitor voltage referred to inverter side. It can be observed that the PLL control strategy forces the inductor current I_L in phase with the inverter voltage under all operating conditions.

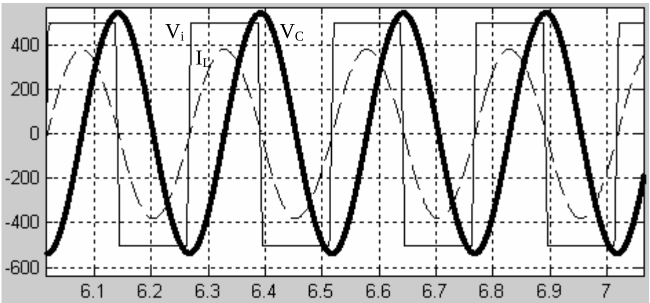

Fig. 8. SIMULINK output inverter waveforms.

The Simulink® was used too for modeling the resonant load and estimates the impedance matching transformer turn ratio. A transformer has a turn ratio windings of 1:4 and the Inductive Coupled Plasma (ICP) torch coil has an inductance L_C of 3.7μH with a series connected 47nF compensating capacitor C_C. The reflected plasma resistance R'_L referred to primary side of the impedance matching transformer is 10.8Ω. The Simulink® resonant load model simulation is shown in the Figure 9.

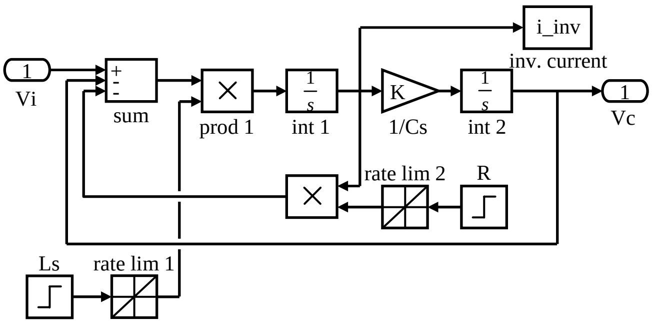

Fig. 9. SIMULINK model for a resonant load.

By other way, for more effective simulation and evaluation of the power circuits, a complete series resonant inverter system was implemented in a PSpice® simulator. This simulation tool is more adequate, because it permits to simulate the inverter power circuits with no ideal devices and introduces parasitic values in the circuit. This is specially important in order to evaluate the parasitic elements [11] influence on the DC bus. In the final simulation all those elements should be incorporate in a way to guide the designer for the best lay-out definition. In these preliminary PSpice simulations this detail level was not considerated and only the IGBTs, diodes and other main power elements were simulated with its commercial device models.

The Figure 10 shows the PSpice diagram circuit.

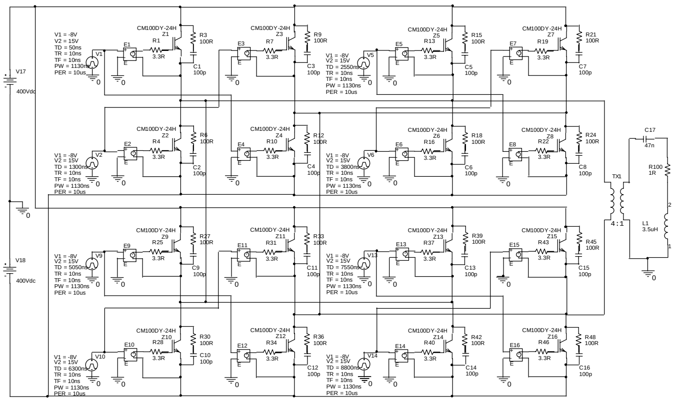

Fig. 10. PSpice simulation circuit diagram.

The Figure 11 shows the PSpice voltage and current waveforms presented by the series resonant load.

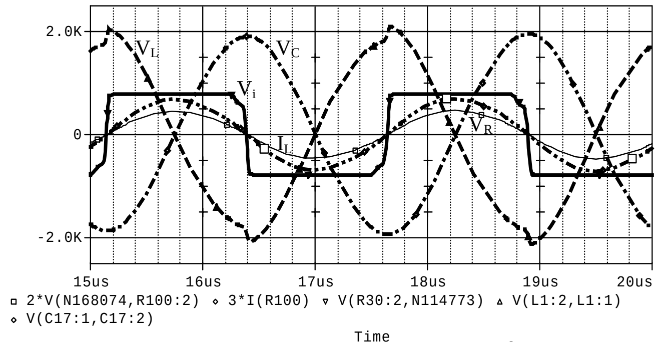

Fig. 11. PSpice series resonant load waveforms.

V_i is the inverter output voltage referred to primary side of the impedance matching transformer and V_C the voltage at the compensating capacitor. I_L and V_R are respectively the current and voltage on the reflected plasma resistance. Note than the waveform deformation on V_L voltage is due to the dead-time discontinuity in the IGBTs switching.

VI. EXPERIMENTAL IMPLEMENTATION

An experimental prototype of the proposed high frequency series resonant converter system has been set up using four SEMIKRON SKM100GB125DN IGBT modules. These IGBT modules incorporate the free-wheeling diodes. Each module is excited by a pair of SKHI 26F driver modules linked to TMS320F2812 DSP evaluation card. This DSP gives a complete development platform programmable in ANSI C language for running on Windows XP® environment. The processor core operates at speed of 150MIPS and the DSP module firmware includes a C++ Compiler, Assembler, linker and Debugger. All connection links to the IGBT power modules are provided by optic fiber cables.

The DC bus is rated to $+750V_{DC}$ and at this time the system have been operated with an output power of 34kW at 450kHz nominal frequency. The global efficiency of the resonant converter referred to load is about 65% under these conditions. The impedance matching transformer is constituted of 16 plane copper coils with a turn ratio windings of 1:4 and standard ferrite magnetic cores. The ICP torch coil is formed by a seven turns of 3/8" copper tubing around the 75mm diameter quartz confinement tube. All experimental tests are being achieved with aid of a 50kW non-inductive resistive load.

In order to improve the global performance of the high frequency series resonant converter and reduce the IGBT turn-off switching losses, new switching strategies and command sequences are being tested. Like this, it is expected a substantial reduction of the harmonic and spurious current contents in the resonant load.

VII. CONCLUSION

The preliminary simulations and results obtained by now evidence the evolutionary potential proportionate by this new topology using resonant inverter modules driven by sequential gate pulsing method. Those results become more significant still if considered the technological improvements that the IGBT NPT devices type should incorporate in their next versions.

For specific applications in high frequencies this new topology arrangement offers a solution seeking to overcome the technological limitations currently imposed by use of the MOSFETs devices, mainly concerning the power handling, reliability and cost. The use of the IGBT NPT devices in this new application field becomes important, particularly in the high power converter project handling RF power above the hundred of kilowatts.

The use of a DSP microcontroller represents an attractive technological solution if considered the involved complexity in the IGBTs command strategy, generation of the command signals and control, as well as the implementation of the several requested functionalities.

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