In this paper a low power (1.8 kW), high frequency (33 kHz), no-flight breadboard of Power Conditioning Unit (PCU) for arcjet application is described. The structure and the main electrical data of the PCU are presented, with particular care to the two fundamental hardware blocks: the start-up unit and the DC/DC converter for the arc supply. The PCU control is described too. Also the control description can be divided in two main blocks: the analog and the digital section. Finally, the start-up control technique is described. After the review of the technical characteristics of the PCU, preliminary tests results on arcjet simulator are presented.

The role of electric propulsion, after the experiences of the 50's and 60's, has become nowadays very relevant. Many efforts have been made to investigate the characteristics of an arcjet thruster assembly. In 1990 BPD started a low power arcjet development program as a part of a more general arcjet development program, awarded to BPD to ESA (European Space Agency) and ASI (Agenzia Spaziale Italiana). Following an ASI contract, BPD as delivered study contracts regarding one of the most important aspects of an arcjet assembly: the Power Conditioning Unit or PCU.
In particular, the PCU theoretical modelling has been commissioned to CENTROSPAZIO (Pisa), while the prototype realization has been assigned to FIAT-CIEI and Ansaldo Ricerche. In order to efficiently operate an arcjet, the PCU must accomplish many tasks: it is required to start the arc, to supply and regulate the arc current, to establish the galvanic insulation between the DC bus and the arc and to adjust the battery voltage to the arc requirement. Those tasks are of course to be obtained with as low weight and high efficiency as possible. In order to obtain those targets, the use of a high frequency inverter is mandatory. On the basis of the studies recently performed the feasibility of a 16-60 kHz PWM inverter based PCU for low power arcjet applications has been widely investigated.[1,2]

In the paper the results relevant to our 1.8 kW, 33 kHz no-flight PCU breadboard are presented.

**PCU structure**

The PCU is basically made of the following main elements: a DC/AC Inverter (VSI-PWM, single-phase bridge inverter), a high frequency ferrite transformer, an AC/DC center-tap single-phase full wave rectifier and an inductive output filter. The hardware schematic is shown in fig. 1. In the following, the main PCU design data are reported.

**PCU design data**

**Inverter.**

The inverter unit supplies the high voltage and current to sustain the electrical discharge through the arc electrodes. The configuration chosen is a full bridge structure. We chose this structure in order to have lower switching losses with respect to the half-bridge (in the full bridge the energy on the stray inductance returns to the supply during the switching), which was a possible alternative. The price to pay for this choice is the required insulated gate drive unit for the upper switching devices. The inverter switches are power MOS. Each switch is made of two Mosfets parallel connected, with 10 mΩ of equivalent Rdson.

The devices have been chosen with a maximum voltage of 200 V; the diode in anti-parallel with the complementary MOS clamps the voltage during the off period to the DC-bus voltage and limits the overvoltages. To this aim particular care has been devoted to the electrical lay-out. The MOS main data are:

<table>
<thead>
<tr>
<th>rating voltage</th>
<th>200V</th>
</tr>
</thead>
<tbody>
<tr>
<td>rating current</td>
<td>79A</td>
</tr>
<tr>
<td>Rdson</td>
<td>20mohm</td>
</tr>
<tr>
<td>equivalent Rdson</td>
<td>10mohm</td>
</tr>
</tbody>
</table>

**Inverter switching frequency**

In order to reduce the weight and size of the whole PCU, the switching frequency has to be as high as possible. The usual limits are 8/10 kHz for laminated iron cores, and 40/60 kHz for ferrite cores. As far as the ferrite cores are concerned, the limits are imposed by the switching losses and EMI requirements. We chose a ferrite core, and the trade-off for our design has been 33 kHz.

**Transformer**

The transformer has been realized using a ferrite core. The turn ratio has been chosen in order to guarantee a suitable no-load voltage, to control the current even when the DC voltage is near to the minimum (50 V). The transformer main data are the following:

<table>
<thead>
<tr>
<th>turns ratio</th>
<th>3.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary voltage</td>
<td>85V (max)</td>
</tr>
<tr>
<td>primary current</td>
<td>53 A (max)</td>
</tr>
<tr>
<td>secondary voltage</td>
<td>297.5V (max)</td>
</tr>
<tr>
<td>core type</td>
<td>E core</td>
</tr>
</tbody>
</table>

**Rectifier**

The rectifier is a single phase, full-wave, center tap structure. This circuit topology has been chosen to minimize the conduction losses due to the diodes. A clamp network limits the overvoltage to 900 V. The clamp network is a little bit more complicated than the usual RC snubbers, but has the advantage to dissipate only the energy associated to the overvoltage.
Moreover the design of the clamp is independent of the stray inductance of the transformer and the reverse recovery of the diodes.

The diodes main data are the following:

<table>
<thead>
<tr>
<th>Id</th>
<th>30 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vrev</td>
<td>1200V</td>
</tr>
</tbody>
</table>

**Output filter**

The value of the filter inductance is determined by the ripple on the output current. We chose an output ripple (maximum) of 1 A. Using this value we have obtained an inductance value of 1.13 mH.

The inductor is made of two coils of 21 turns, mounted on the two legs of an E-shaped ferrite core.

The inductor main data are the following:

<table>
<thead>
<tr>
<th>current (max)</th>
<th>22.5A</th>
</tr>
</thead>
<tbody>
<tr>
<td>inductance</td>
<td>1.13mH</td>
</tr>
</tbody>
</table>

**Start-up Unit**

The principle circuit of the start-up unit is shown in fig. 2.

The start-up circuit consists of an auxiliary winding on the output filter L1 that energizes the magnetic circuit of the output inductor. When the switches Swacc1 and Swacc2 (see fig. 2) open the magnetic circuit stored energy keeps constant and causes an overvoltage, reflected on the main winding of the inductor, multiplied by the turn ratio. [3]

A clamping circuit is implemented, which has the tasks to sink the current if the arc does not ignite and to limit the voltage to 4.5 kV.

The switches are still MOS (15 A, 1000 V), two in parallel.

The Start-up unit ratings are:

<table>
<thead>
<tr>
<th>voltage</th>
<th>max 4.500 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>current (initial)</td>
<td>10 A</td>
</tr>
<tr>
<td>energy</td>
<td>50 mJ</td>
</tr>
<tr>
<td>turns ratio</td>
<td>6</td>
</tr>
<tr>
<td>primary inductance</td>
<td>31 μH</td>
</tr>
<tr>
<td>ignition voltage supply</td>
<td>50-85V (dc bus)</td>
</tr>
</tbody>
</table>

**VMOS rating**

<table>
<thead>
<tr>
<th>Vds</th>
<th>1000 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rdson</td>
<td>0.6 ohm</td>
</tr>
<tr>
<td>equivalent Rdson</td>
<td>0.3 mohm</td>
</tr>
<tr>
<td>current</td>
<td>15 A</td>
</tr>
</tbody>
</table>

Fig. 2 Start-up circuit schematic.
PCU Control

We can schematically distinguish between the start-up unit control and the DC/DC converter control (modulator).

Start-up unit control

The starting technique is a Pulse Width Modulation conditioned by the (measured) value of the current. The arc ignition requires the inductance to be charged with a current of about 60A. When the required current value is achieved (the measure is made by means of a suitable current transformer (TA)), the switch is open with the consequent overvoltage.

There is a fixed limit to the auxiliary switch on time, in order to respect the energy constraints and to avoid abnormal operations deriving from measurement or power circuits disturbance.

The start-up unit time constraints are:

<table>
<thead>
<tr>
<th>on period</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>repetition period</td>
<td>250 ms</td>
</tr>
</tbody>
</table>

DC/DC converter control (Modulator)

During the design phase three different control techniques have been evaluated:

Direct duty ratio Pulse Width Modulator with PI regulator.

This is a fixed frequency control, where the control voltage controls the duty ratio of the switches by comparing the error signal to a fixed frequency sawtooth waveform

Current mode control:

a) Hysteresis Modulator (delta modulator).

This technique allows a fixed current error and as a consequence the switching frequency is variable; a variation range (hysteresis band) for the load current is fixed.

A suitable comparator forces the commutations when one of the limits is achieved.

b) Peak current mode modulator.

This is characterized by a fixed switching frequency and a variable duty-cycle; the switch is turned on at the beginning of each constant frequency switching time period.

The control voltage dictates the instant at which the switch is turned off; it remains in this state until the beginning of the next switching cycle.

Then main problems which have been considered in the design phase are: current overshoot, EMI disturbance, efficiency, static and dynamic precision.

On the basis of the simulation results relevant to the previous problems, we choose the last one control technique.

The principle schematic of the control is shown in fig. 3.

Modulator description

The modulator can be divided in two parts: the analog section and the digital one.

Input signal for the analog section are the reference current $I_{ref}$, the arc current $I_{arc}$ and the transformer primary current $I_T$ (see fig. 3).

The analog section compares the reference current and the actual output current $I_{load}$.

The error signal is fed to a PI (Proportional-Integrative) regulator.

The inverter switching frequency is controlled by a clock in the digital section; this commands the duty cycle on the basis of the (digitalized) values of the analog comparator.

The operating logic is the following.

At the beginning of each half-period a first diagonal is turned on.

The inverter output current is the sum of two different current; the first one is the arc current multiplied by the turn ratio; the second one is the transformer magnetizing current.

The inverter output current is compared with the sum of two other current, the set point current (requested arc current) and an offset current. When the inverter output current is greater than this sum the diagonal is turned off.

The same thing is done for the other diagonal in the second half-period. If the diagonal is still on at the end of each half-period, it is turned off before the other one is switched on.
The offset current (10% max of the reference current) is the output of a PI regulator and provides cancellation of the static error due to transformer magnetizing current.

Inverter's diagonals (Da and Db) On/Off cycle is about of 15 μs since the total period is 30 μs.

The clock frequency is obtained dividing by four the oscillation of a 4MHz quartz; a perfect symmetry is hence obtained.

The On/Off state signal (output of a FF J/K) is delivered to the right inverter diagonal. For the switch's protection, a dead time of 1 μs has been established, so after 14 μs from the on signal starter the time base generates a diagonal commutation.

A slope compensation circuit has been added to the control to provide stability and to prevent subharmonic oscillations, which is a typical problem of current mode controls.

We have still considered the possibility to make use of dedicated integrated circuit (e.g. UC1846 or similar) which carries out much of the digital and analog implemented function.

We did not make this choice because a "discrete" approach allows a wider control of parameters and can be easily implemented in a hybrid circuit for the flight version of the PCU.

A dedicated circuit monitors the supply voltages; when the supply voltages decrease under 12V there is a MOS command inhibitions; in addition, this control provides a logic reset each power-up.

**Control board power supply**

The control board is supplied by a resonant switching DC/DC converter.

We choose a resonant configuration in order to have lower filtering requirements and a reduced EMI level.

The main data of the power supply are:

<table>
<thead>
<tr>
<th>Input voltage</th>
<th>50-85 Vdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>four ±15 Vdc (2.150mA, 1.300mA, 1.500mA)</td>
</tr>
</tbody>
</table>

The resonance frequency is fixed at 100 kHz.
**Preliminary test result**

The test of the PCU on the real arcjet are starting now. The PCU is now at BPD facilities for the tests on the real arcjet thruster. [4]

The preliminary results presented in this paper are relevant only to the start-up circuit verification, operation at nominal point and efficiency.

The results have been carried out on the arcjet simulator at the FIAT-CIEI facilities, where has been realized the integration between the PCU and the arcjet simulator. [5]

Fig. 4 and 5 gives an idea of the physical structure of the PCU.

**Start-up circuit verification.**

The start-up circuit characteristics have been analyzed.

In fig. 6 is shown the PCU output voltage with disabled inverter (in order to simulate the energy absorption of about 50 mJ, a load resistor of 900 Ω has been selected).

Notice that both energy and impulse are in conformity with design's specifications.

**Operation at nominal point**

The PCU static and dynamic behaviour have been analysed. A complete absence of overshoot in the current and a very short settling time have been proved. In fig. 7 the PCU current is 12A with a supply voltage of 50V and resistive loads equal to 5.5 and 9 Ω. In both cases the static error is null. Fig. 8 shows the PCU's start with an output current of 16A; the load is the arc simulator which is set for an output voltage of 100V and the PCU is supplied with a laboratory power supply.

![PCU control board](image1.png)

![PCU power supply](image2.png)

![Input wires](image3.png)

![Output wires](image4.png)

**Fig. 4 PCU mechanical schematic.**
As can be seen the PCU responds in about 100 $\mu$S without any overshoot. Note that the current in the PCU is independent of output voltage.

In fig. 9 the PCU's load is the simulator functioning as negative resistance. As shown in fig. 9, a highly stable operation has been achieved, together with static precision and absence of overshoots after the commutations.

**Efficiency**

As far as the efficiency is concerned, the results are quite satisfactory. We obtained an average efficiency of 88% (dependent on the load conditions), with respect to the 90% established as a target for the design. We are confident that with minor modifications the design target can be obtained.

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**Fig. 5** PCU physical appearance.

**Fig. 6** PCU output voltage during start-up.

$t = 1 \mu$S/div, $V = 900$ V/div

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**Fig. 7** PCU operation at nominal point.

$t = 20 \mu$S/div, $i = 5$ A/div

$i_{ref} = 12$ A, $V_{dc} = 75$ V

$R_{load} = 5.5 \text{ ohm (upper)}$

$R_{load} = 9.0 \text{ ohm (lower)}$
Conclusion

In this paper the main electrical characteristics and the control principles of a Power Conditioning Unit no-flight breadboard have been described. Preliminary tests results performed on arcjet simulator are shown too. The preliminary test results indicate a good static and dynamic behaviour of the PCU control. The PCU is now starting the test on the real arcjet.

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References


