POWER ELECTRONICS FOR SPACE AND ITS FALL-OUT TO GROUND

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ABSTRACT

The efforts to optimizing energy conversion and distribution on board satellites pioneered the development of circuit topologies, modeling, and control techniques for power processors and much influenced the origin and the shape of modern power electronics. Nowadays, space applications continue to provide solutions of new technical problems and the paper illustrates how a few recent projects pushed improvements of the analyses techniques and of new computer-aided design tools. This achievements are briefly described and their usefulness for the design of ground power electronics circuits and systems emerge.

I. INTRODUCTION

The origin and the fast raise of power electronics as a new and important branch of electronics dates back to the 70's and has been pioneered by technical staffs involved in the design of energy sources and processors for space satellites.

In those years, the averaged state space models for switched power converters were proposed together with new control techniques, power devices and original circuits topologies.

The community of specialists in the Space Power Electronics had an important role in the foundation and in the growing up of the IEEE Power Electronics Group that, later on, at the end of the 80's created the Power Electronics Society.

Space Applications continue to be a driving force of the evolution of power electronics and to benefit a large number of ground applications in the fields of consumer, industrial, communications and military electronics.

Hereafter, the authors depict their personal experience on this matter; similar cases happened in many others laboratories everywhere in the world.

Three projects in the last years strongly influenced the direction of the electronics research group at the University of Milan (UNIMI): GlobalStar power supply sub-system, Power Distribution Assembly for the International Space Station, High Voltage Sources for Ionic Motors.

_ GlobalStar is a satellite-based, wireless telecommunication system designed to provide global position, voice, data, fax, messaging and other services to users worldwide. 48 GlobalStars satellites and four spares have been placed into low-earth-orbit. They turn within eight orbital planes of six satellites each with a 1414 kilometres circular orbit 52 degrees inclined.

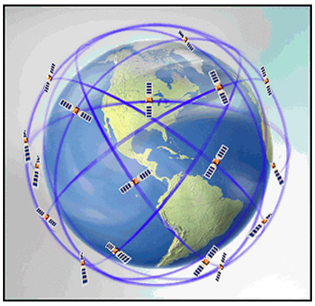


Figure 1: GlobalStar cluster for GPS and telecommunication services.

The satellite primary power source comes from the sun light collected by two solar arrays, and batteries are employed to provide power during the eclipses. The satellite mass is approximately 450 kilograms and it requires about 1100 watts for normal operations.

The sub-system consisted in a DC-DC boost converter driving a push-pull soft-switched transformer with multiple low voltage outputs.

_ The International Space Station (ISS) is the largest platform put in orbit until now. One of its facilities is the Remote Power Distributions Assembly (RPDA), a configurable Standard Payload Outfitting Equipment that distributes the 120VDC bus and a 28VDC galvanic isolated e.m.f. to the payload racks [2-3].

_ Ionic Motors are going to be widely employed for satellite asset regulation and orbit recovery instead of pressurized hydrazine thrusters. They eject accelerated ions taking energy from an HV DC source whose design is severely conditioned by requirements of robustness, efficiency and reliability.[4,7,10]

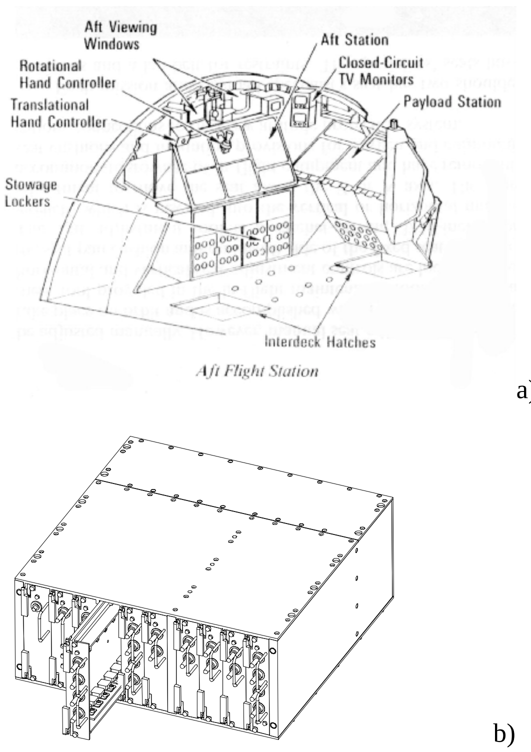


Figure 2: a) ISS Air Flight Deck, 40 square feet large approximately; b) RPDA housing.

The design of the HV generator is made more difficult by the unavailability of an accurate electric model of the motor.
The UNIMI electronics research group was partner of Italian industries in all the three mentioned projects; the industries were official contractor and responsible for products.

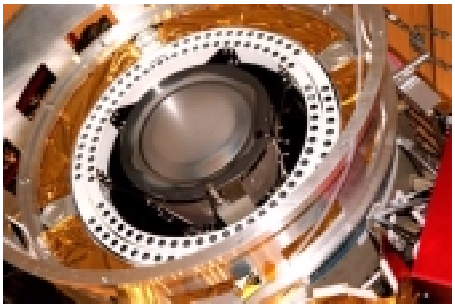


Figure 3: A picture of Ionic Motor in the satellite assembling laboratory.

II. MODELING THE POWER CONVERTERS

Just to begin with an historical overlook, reference is made to the simple circuit in the Fig. 4 which is the switching cell of a step-down converter, the so called "Buck".

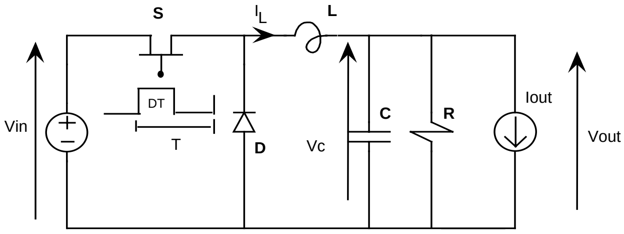


Fig.4: Buck converter power cell.

As usual the small letters will indicate the perturbations of the electric variables and vectors **x, u, y** will collect the state variables**,** the inputs and the outputs respectively:

$$\mathbf{x} = \begin{bmatrix} i_l \\ v_c \end{bmatrix} \qquad \mathbf{u} = \begin{bmatrix} v_{in} \\ i_{out} \\ d \end{bmatrix} \qquad \mathbf{y} = \begin{bmatrix} i_{in} \\ v_{out} \end{bmatrix}$$

The dynamic description in terms of linear first order differential equations can be put in the form:

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \end{cases} \tag{1}$$

The linear system (1) is the state space description and it allows to express all of the transfer functions by the frequency depending matrix:

$$\mathbf{H}(s) = \left[\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D}\right] \tag{2}$$

For the Buck converter in the Fig.4 the state space matrices **A**, **B**, **C**, **D** are:

$$\mathbf{A} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} \frac{D}{L} & 0 & \frac{V_{in}}{L} \\ 0 & \frac{1}{C} & 0 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} D & 0 \\ 0 & 1 \end{bmatrix} \qquad \mathbf{D} = \begin{bmatrix} 0 & 0 & I_{L0} \\ 0 & 0 & 0 \end{bmatrix}$$

Schematics in the figures 5,6 and 7 represent different power processors designed and realized for the three application cases mentioned in the introduction.
The analysis and the control optimization of such circuits can not be afforded on the sole base of the averaged state space models in the continuous time and in the Laplace transform domain according to (1) and (2). Better suited is the description in the discrete time and in the Z-transform frequency domain.
A system of algebraic difference equations substitutes (1):

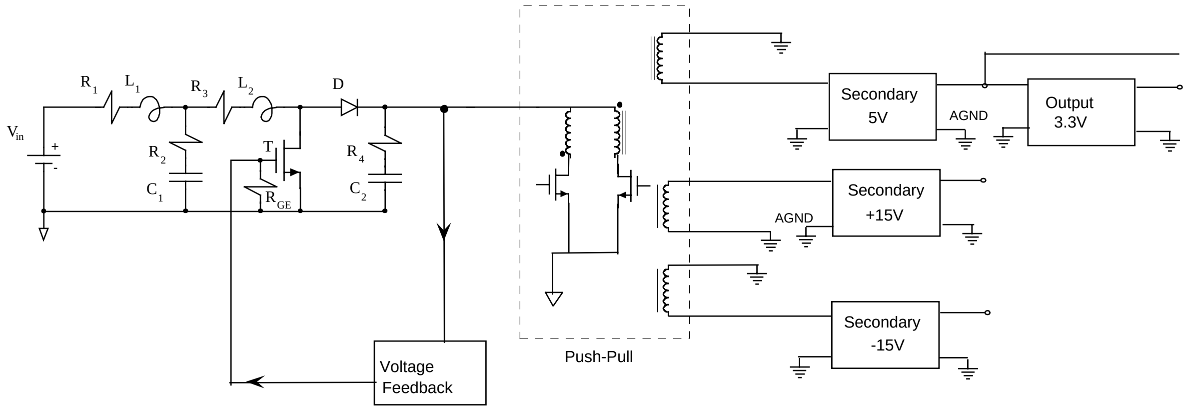


Figure 5: Multiple-output isolated Boost for GlobalStar.

$$\begin{cases}\mathbf{x}[(k+1)T]=\mathbf{Ax}[kT]+\mathbf{Bu}[kT]\\ \mathbf{y}[kT]=\mathbf{Cx}[kT]+\mathbf{Du}[kT]\end{cases} \quad (3)$$

and the transfer function matrix becomes:

$$\mathbf{H}(z)=\left[\mathbf{C}\left(z\mathbf{I}-\mathbf{A}\right)^{-1}\mathbf{B}+\mathbf{D}\right] \quad (4)$$

where T is the switching period and $z=e^{sT}$,[11].

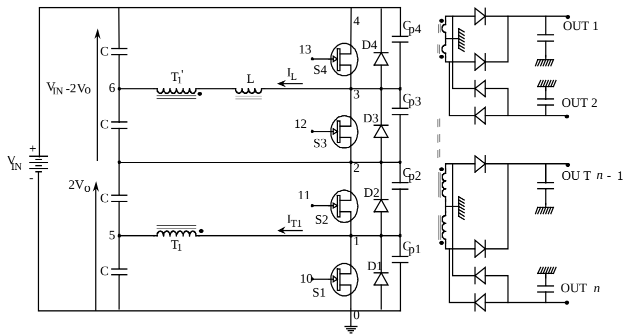


Figure 6: Switching cell of the phase-shifted DC-DC converter for the ISS RPDA.

The state space model in the discrete time for the circuits shown in this page represents a complicate an tedious task for the designer if he has to build up it analytically by himself.

The exigency arises to own an automatic tool providing the models, possibly such tool should help the assignment of the feedback, either external or inner, and of the feed forward compensations. Moreover the capacity of modeling the connection of circuits is claimed for reaching the closed loop transfer functions and the characterization of complex power systems.

III. AUTOMATIC DYNAMIC MODELING AND CAD TOOL

A response to the needs for analysis and design of space power converters has been given by the development of an automatic modeling and design software tool named FREDOMSIM (FREquency DOMain SIMulator, FDS in the following) [1,5,6,].

The dynamic modeling and the aid to the control optimization of DC to DC converters constitutes its most frequent application [8,9].

FDS automatically gets the state space matrices in the discrete time of a given circuit starting from its transient analysis in the PSpice simulation environment.

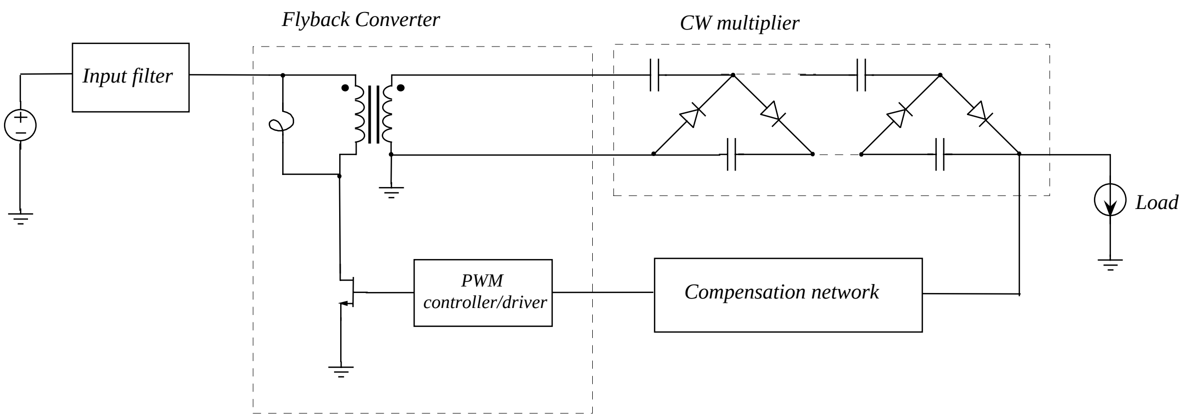


Fig.7: Block scheme of HV DC generator for ionic motors.

The capabilities of the developed tool are hereafter summarized in relation to the circuit in Fig.5.

The input voltage spans from 14 - 23 Volt, the maximum output power is 20 Watt, the switching frequency 131 kHz and the Boost output voltage 30 Volt.

The dynamic analysis is based on the power cell in the Fig. 8 which represent the circuit of Fig. 5 without any external or internal feedback; furthermore the loads of multiple outputs are represented by an equivalent reflected load (R_{LOAD}, I_{OUT} and C2) at the Boost output port.

The main steps of the FDS assisted analysis and design optimization are:

- PSpice Schematic entry of the switching circuit with the feedback loops open
- Automatic solution for the steady state
- Delivery of the state space matrices **A**, **B**, **C, D**, of the z-transform transfer functions and of all the frequency responses. In the Fig. 9 module and phase of the control-to-output transmission are plotted versus frequency

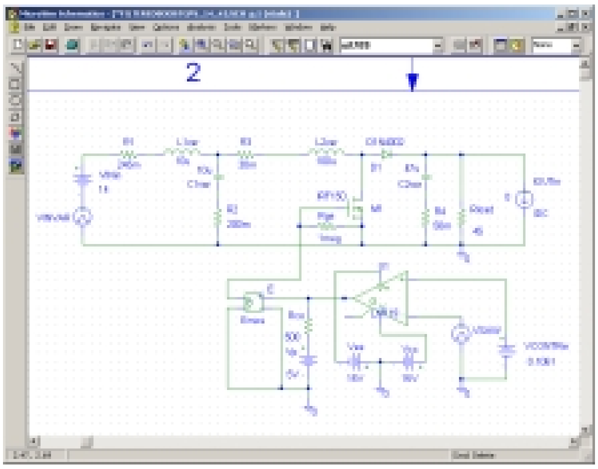


Figure 8: Pspice schematic entry of the Boost power cell.

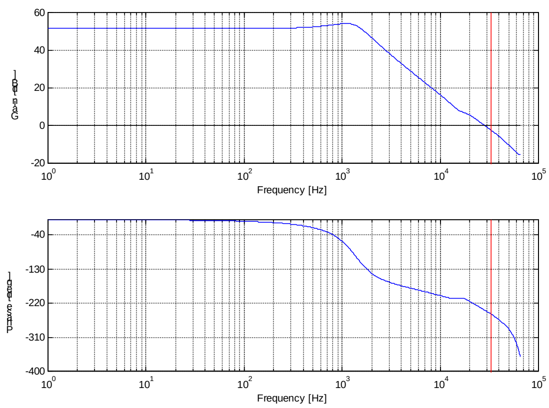


Figure 9: Control-to-output frequency responses.

- Aid to the assignment of the inner feedback from the state variable I_{L2} to the control input.

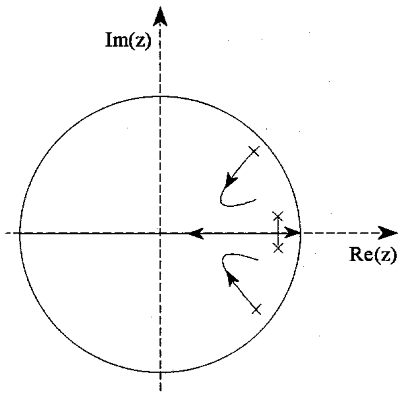


Figure 10: Root locus in the Z plane where the inner feedback coefficient is the variable parameter.

According to Fig. 10, the optimum value of the inner feedback coefficient corresponds to a couple of real poles and to a couple of complex poles positioned on the buy point of the root trajectories, where resonance damping is maximum. The result can be appreciated in the Fig. 11.

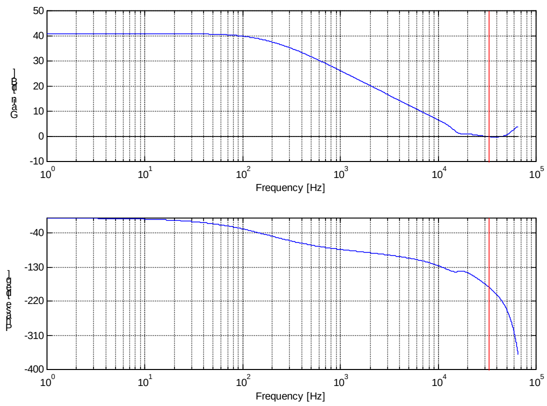


Figure 11: Improvement of the control-to-output frequency response by means of inner feedback (current mode).

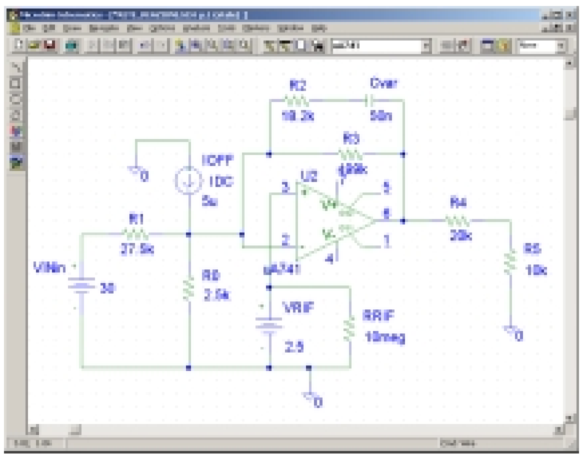


Figure 12: Pspice schematic entry of the external feedback network.

The external feedback network is shown in the Fig. 12.
The resulting loop gain frequency response is reported in the Fig. 13.

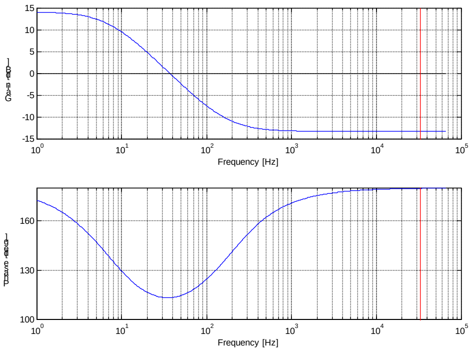


Figure 13: Module and phase of the loop gain versus frequency.

In the MATLAB/SIMULINK environment the connection of the Boost power cell with the external feedback network is made as shown in the Fig. 14.

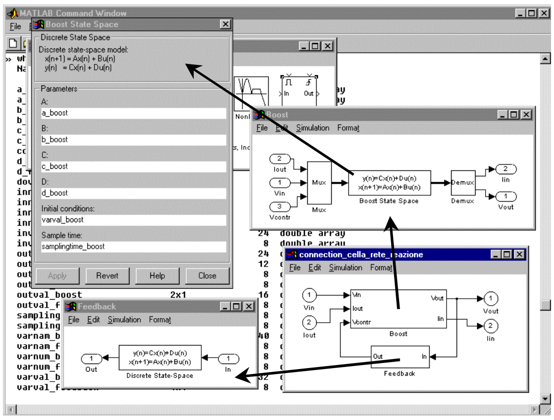
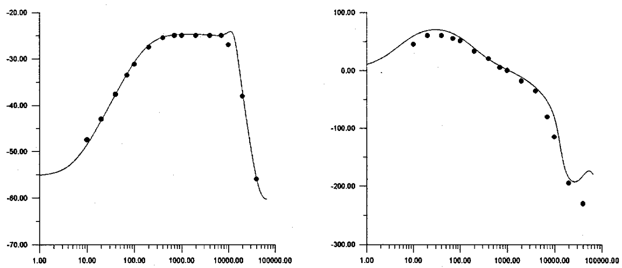


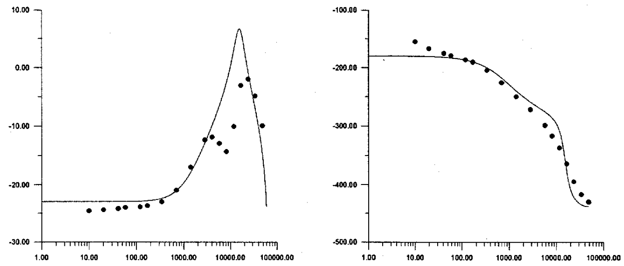
Figure 14: Feedback loop closure in the MATLAB/SIMULINK environment.

The closed loop transfer function are then drawn as shown in the figures 15 and 16. There, the forecast of the module and phase frequency responses for audio-susceptibility and for input admittance are plotted together with relevant experimental data indicated by dots.



(a) (b)

Figure 15: Forecasts and measurements of module (a) and phase (b) of audiosusceptibility versus frequency.



(a) (b)

Figure 16: Forecasts and measurements of module (a) and phase (b) of input admittance versus frequency.

III. CONCLUSION

A number of solutions that matured in the field of power conversion on board satellites, reached an high level of accuracy in the analysis and simulation of power circuits, including switched capacitor ones.
Help in the assignment of inner feedback and feed forward compensation also comes out.
The burden of the designer is significantly reduced by tools providing automatically the small signal models of time variant networks, f.i. FDS.
All this technical achievements can be appreciated in a large number of ground applications.
The UNIMI electronic group took advantage of FDS and related CAD tools in several cases:

- Hybrid switching power supplies design
- Optimization of smart-power ICs
- Wide bandwidth HV generators for high resolution CRTs
- Impedance characterization of inverter fed induction motors
- Dynamic stability forecast of electronic systems constituted by the interconnection of many processors.

The fertilization of space power electronics goes on.

ACKNOWLEDGEMENTS

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