STUDIES IN ELECTRICAL AND ELECTRONIC ENGINEERING 45

Pulse Width Modulated (PWM) Power Supplies

VALTER QUERCIOLI

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To
my wife Patrizia,
my son Marco
and
my parents,
who were robbed
of too much time

Valter Quercioli was born on July 15, 1963. He received the Laurea degree in electrical engineering (M.S.E.E.) from Politecnico di Milano, Milano, Italy, in 1989.
He is presently working as the Head of the Instrumentation Section at the Research and Development Division, Nuovo Pignone, Florence, Italy. From 1988 to 1990 , he worked in the Switching Power Supplies Department at Plessey's plant located in Terranuova Bracciolini (Italy) as a junior designer. From 1990 to 1991 he was with European Space Research and Technological Centre (ESTEC) in Noordwijk an zee (The Netherlands) as a researcher in the Spacecraft Power Conditioning Department.

Introduction.

This book is about a restricted class of power supplies: the so-called Switching Mode Power Supplies (SMPS), which make use of the Pulse Width Modulation (PWM) technique to operate. Even if it is restricted, such a class of power supplies is fairly large because most of modern electronic equipments (computers, telecoms, instrumentation, etc.) make use of this technology to supply the electronic boards. The main reasons are large efficiency, minimum physical size and minimum weight so that smaller and reliable supplies are achieved.

Neverthless, the design of an SMPS is not a trivial process since a lot of knowledge is involved in: circuit theory, semiconductor devices theory and technology, magnetics theory and technology, linear and nonlinear control theory. All this very specialistic knowledge can be earned only after a lot of hard work both in study and practice, so that people need a lot of time to become good SMPS designers.

This book is a little attempt to give SMPS designers a tool by which the learning time can be shortened and, moreover, useful informations about SMPS design process.can be easily found.

The book is made up of seven chapters. The approach to SMPS design is of the *systemic* type, that is the SMPS equipment is subdivided into functional blocks whose properties and relationships with the other functional blocks are studied.

Chapter 1 is just an introductory chapter, where the SMPS functional subdivision is outlined. The reader will understand, then, that some problems rise due to the interactions between the SMPS and both the mains network and the electrical loads. In order to minimize such interactions, a controller is needed to regulate the output voltage and/or the output current. Moreover, the controller must ensure a sufficiently good dynamic performance to avoid bad operations on the electrical loads. Some types of control techniques are then introduced.

Chapter 2 deals with the functional block which must ensure a sufficiently good decoupling between the SMPS and the mains network: *the input stage*. Because the SMPS is a highly nonlinear equipment both current harmonic distortion and electrical noise are generated which heavily affects other electrical loads linked at the same mains network. A suitable decoupling filter must be provided. Such a filter is called an *EMI* (ElectroMagnetic Interference) *suppression filter* and it is one of the hardest electrical circuits to design. Some basic concepts are provided about the design of such a filter because the designer must be aware of the importance of the mains network decoupling problems but more specialistic knowledge is required so that a sufficiently large bibliography is reported in the references.

Chapter 3, 4 and 5 deal with three different types of power stages: *Flyback, Forward and Push-Pull converters*, with their relevant variants. These type of converters have been chosen because they are widely used in industrial, civilian and military applications. Non isolated converters (Buck, Boost and Buck-Boost topologies) are not treated because most of the existing books about SMPS design already deal about them. On the other hand the design of isolated converters (Flyback, Forward and Push-Pull) need a deeper understanding of the complex interactions between the parasitic parameters of the devices (especially semiconductor switches and magnetics) and it is not easy to find out books which face these problems in the particular context of SMPS and its real waveforms.

Chapter 6 deal with the *output stage* which can be made up of an *output filter* and a *postregulator*. The output filter can be of the capacitive type (C filter) or of the inductive-capacitive type (LC filter), depending if the output current from the power stage to the load(s) and the output capacitor(s) is impulsive or unidirectional, respectively. Further, the filtering properties heavily depend on the capacitor technology. Thus calculations of the output voltage ripples are made for different capacitor technologies: electrolythic, plastic, ceramic.

Some pages are devoted to the study of one of the most difficult components to deal with: *the coupled inductor*. Whenever possible the coupled inductor should be used on multi-output converters because of the better performance relative to the indipendent inductors case. On the other hand, good performance, especially from cross-regulation and stability points of view, are possible only when the behaviour of such a device is well understood, which justify the large number of pages devoted to this topic.

Postregulators are needed all the times that tight voltages are needed on multi-output converters whose cross-regulation is not sufficiently good. A particular class of postregulators are increasing in their importance: *the magnetic amplifier*. A quite large number of pages are devoted to this topic either from a device design and control loop design points of view.

At this point the reader has understood how the design of the power stage of an SMPS is performed and how to face the problems with the mains network. Now control problems mut be faced. In fact, to cope with mains network disturbances and electrical loads variations, some kind of control must be provided on the SMPS output voltage and/or output current. On the other hand an SMPS is a nonlinear device so that the control problem is quite difficult to cope with in a formal way. A linearization is mandatory which should be sufficiently accurate in the frequency range of the disturbances. Thus, after a reminder on linear systems control theory, a special linearization method is described: the *state space variables averaging*. By this method a quite accurate low frequency linear model of the power stage is provided so that the control problem can be solved with the use of the classical techniques of Proportional, Integral and Derivative (PID) controllers. If only the output voltage is controlled a Voltage Mode loop control is performed; if the output current too (or a current directly related to it, usually the inductor current) is controlled, a Current Mode loop control is performed. Whenever current mode control is performed, a multi-loop controller design is made. Four control techniques are deal with: *direct duty cycle, input voltage feedforward, average inductor current (conductance control), peak inductor current (peak current control)*, with all their problems. Two minor problems occuring in the voltage loop design are deal with: the Right Half Plane Zero (RPHZ) and the isolation of the loop by the use of optocouplers.

Finally, an index of the output voltage stiffness against load variations is introduced: *the output impedance* of the SMPS. This parameter is very important to be known because once the SMPS has been designed, the voltage loop bandwidth must be chosen by a suitable trade-off between such a parameter and a loop stability index (usually the phase margin).

Lastly, a quite comprehensive list of references is delivered the reader should refer to for every desired deeper investigation. All the quoted papers are quite basic, that is they are the papers over which the researchers worlwide have worked to develop knowledge in SMPS.

Throughout the book a reference to MOSFET (Metal Oxide Semiconductor Field Effect Transistors) semiconductor switches is made. The reason of that is because most of SMPS market is in the power range up to one kW, with low input voltage (up to 400V). Within this range MOSFETs are very suitable. Moreover, this type of switch has far less switching problems than bipolar switches (BJT, Bipolar Junction Transistor) so that, whenever possible, the choice of MOSFETs rather than BJTs in modern SMPS is almost mandatory.

Finally, capital letters (e.g. V_{in}, D, I_L) are used to indicate steady-state quantities, while small letters (e.g. v_{in}, d, i_L) are used to indicate quantities which depend on the time (which means $i_L = i_L(t)$, or $d = d(t)$). Small letters with a circumflex stress are used to indicate quantity variations (e.g. $\hat{i}_L = \Delta i_L$), which shall be an useful notation especially in the control theory (chapter seven).

The author wish to acknowledge the following people for their unevaluable support either material and moral: Mr. L.Ghislanzoni and Mr. M.Martella from ESTEC (The Netherlands), Mr. A.Canova from Magnetek (ex-Plessey, Italy), Mr.G.C.Esposito, Mr.V.Mezzedimi and Mr.P.L.Nava from Nuovo Pignone (Italy). A very special thanks to my wife Patrizia, my son Marco, my parents, my parents-in-law and Don.F.S.Bazzoffi for their patience, which was severly tested, and moral help.

Florence, 1993 *Valter Quercioli*

Contents

Chapter 1.

The power supply system.

All electronic devices need a power supply in order to operate. Usually a dc supply voltage is delivered to the device and a dc current is taken by it which depends on the absorbed power. Thus all electronic equipment and systems clearly need at least a *power supply* equipment or board, integrated within themselves, in order to operate.

There are only two possible power sources the energy can be taken from: *dc batteries*, and the 50Hz (or 60Hz) *power mains*. The energy sources are of such a nature that electrical perturbations and faults can occur at the delivery point (transient overvoltages, lightning and so on), while the electronic equipment is so delicate that no supply voltage perturbations can be withstood. Moreover, some *electronic loads* (that is, any electronic equipment supplied by the power supply) themselves cause perturbations (e.g. electric motors and their electronic drives) so that the power sources need to be protected against them in order to prevent noise and disturbances to nearby equipment and systems.

Hence, a power supply must be able to perform the following basic tasks:

- to deliver suitable dc voltages to electronic equipment and systems, from now on called *loads*, by changing the energy supplied by power sources such batteries or mains, from now on called *lines*;

- to decouple the load from the line (or vice versa) in order to prevent any electrical interaction between them.

A very simple conceptual sketch is the following one

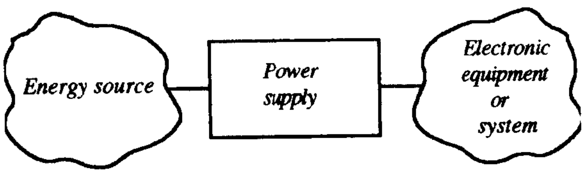

Fig. 1.1: The power supply concept

Power supply parameters. From a very basic point of view, the line can be modelled as a suitable dc voltage source (perhaps with a superimposed voltage ripple at some frequency), from now on called the *input voltage* v_{in}, with its own *internal impedance* Z_{in}. In the same way, the load can be considered as a suitable variable resistor, called the *load resistance* R_L. Thus a power supply can be thought of as an equipment that must interface the line source to the load resistance in such a way that a very constant dc voltage, from now on called the *output voltage* v_{out}, is applied to the load resistance itself, independently of any perturbation that can occur either on the line side or the load side. On the other hand the energy source can be either a dc battery or 50Hz (60Hz) ac power mains. If the latter is the case a suitable ac/dc converter (usually a simple Graetz's bridge cascaded by bulk capacitors) must be integrated within the power supply equipment.

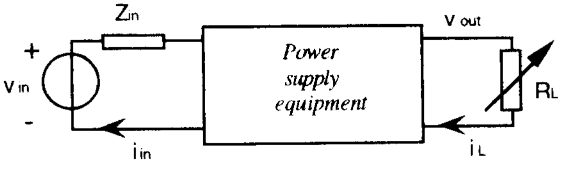

Fig. 1.2: Power supply connections

From Fig.1.2 it is easy to understand that at least two parameters are needed to characterize the power supply:

- *line sensitivity*;
- *load sensitivity*.

In fact, the output voltage v_{out} is tied to both input voltage v_{in} and load resistance R_L by a function of the type

$$v_{out} = f(v_{in}, R_L) \tag{1.1}$$

The line sensitivity T_{line} is defined as the output voltage variation when a perturbation occurs on the line voltage.

$$T_{line} = \left(\frac{\partial v_{out}}{\partial v_{in}} \right)_{R_L \text{ const.}} \tag{1.2}$$

The load sensitivity T_{load} is defined as the output voltage variation when a change in the load resistance occurs.

$$T_{load} = \left(\frac{\partial v_{out}}{\partial R_L} \right)_{v_{in}\ const.} \qquad (1.3)$$

The sketch of Fig.1.2 can be improved by considering the power supply block as a two-port device, so that three further quantities (that depend on frequency) should be known in order to understand the right behaviour of the supply itself:

- *transfer gain* T_g;

- *input impedance* Z_{input};

- *output impedance* Z_{out}.

It is easy to see that:

- the transfer gain is effectively the line sensititvity T_{line} (neglecting the effects of the line's internal impedance Z_{in}), so that it should be kept as low as possible; at dc it should be valued

$$T_{g(dc)} = \frac{V_{out(dc)}}{V_{in(dc)}} \qquad (1.4)$$

If the ac transfer gain is low, a low line sensitivity is assured (and the line-to-load decoupling);

- the input impedance should be kept very low because every noise current passing through it causes a voltage noise at the input port that is reflected back to the power source;

- the output impedance can be related to the load sensitivity T_{load} by the simple relationship (where R_L is at the relevant steady value)

$$T_{load} = \frac{V_{out(dc)}}{R_L} \frac{Z_{out}}{Z_{out} + R_L} \qquad (1.5)$$

This formula means simply that if a low output impedance can be achieved, a low load sensitivity is guaranteed.

Hence, we can already say that power supply equipment must have a very low line sensitivity and a low output impedance in order to perform well. Both can be accomplished by a suitable closed loop controller, as will be seen later.

On the other hand a power supply must be able to recover quickly from any output voltage perturbation that can occur. This means that its *frequency bandwidth* should be as high as possible. Some examples of perturbations are switch-on transients, load perturbations, line perturbations and so on. Further, the transient recovery must happen without, or with very little, over(under)shooting and steady error. Thus dynamic parameters such as *overshooting*, *settling time*, *delay time*, *rise time* and so on (applied to the output voltage waveforms) should be defined as precisely as possible by the supply user, in order to give the designer an idea of the performance the supply should provide. Below is a sketch of the most common dynamic parameters:

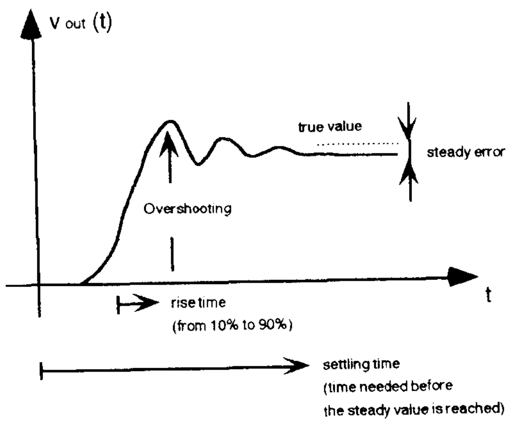

Fig. 1.3: Dynamic parameters

Finally, a very important parameter characterizing a power supply is the *efficiency* η, defined as the power avaiable to the load divided by the power taken from the line:

$$\eta = \frac{P_{out}}{P_{in}} \tag{1.6}$$

The efficiency is very dependent on the type of power supply and most of the effort in modern designs is to increase this parameter. In fact higher efficiency means:

- lower volume, size and weight of the supply;

- lower dissipated power, which in turn means a less stringent cooling design and thus again heavily affects the system size.

Linear vs. switching power supplies. From a fundamental point of view, there are two basic ways to control the output voltage so as to guarantee its stability at the rated value against any line and load perturbations. Both need some feedback from line and load in order to sense those perturbations and to allow the supply's controller to counteract them by a suitable control quantity, as shown below

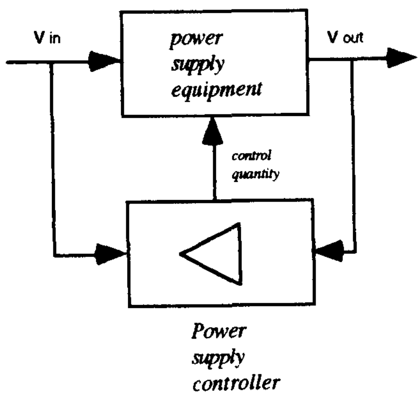

Fig. 1.4: Power supply' control structure

The first way: a suitable variable resistance can be effectively interposed between the dc line and the load resistance. Such a variable resistance is called the *controlling resistance*, because the supply's controller adjusts its value in order to achieve a steady output voltage. Of course the controller will sense both line voltage and output voltage, following the scheme of Figs.1.4.and the resulting 1.5:

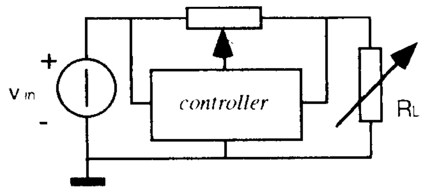

Fig. 1.5: Linear power supply concept

The control action is provided by the voltage drop across the controlling resistance, so that when a perturbation on either the output voltage or the line voltage occurs the excess (either positive or negative) voltage will be absorbed by the controlling resistance itself, as a variation in its own voltage drop. Unfortunately the controlling resistance is traversed by the whole load current so that a power dissipation given by the product "drop voltage multiplied by load current" occurs. It is very easy for the dissipated power to have the same magnitude as the output power; hence a very poor efficiency should be expected. On the other hand the frequency bandwidth of such a type of supply is very high, limited only by the component in the control chain having the lowest frequency bandwidth (usually the controlling resistance, implemented by one or more power BJT).

The second way: the dc line voltage can be transformed into a pulse train of a fixed frequency (usually as high as tens or hundreds of KHz) called the *switching frequency* and variable *duty cycle* (the ratio between the on-time t_{on} and the period T of the pulse). The pulse train is generated by a switching device, possibly scaled up or down by a high frequency transformer, and finally filtered by a suitable low pass filter whose frequency bandwidth is very low (a few hundred Hz) so that just the dc frequency component of the pulses is allowed to pass (and a very small switching frequency component, called the *ripple voltage*).