Application and Integration Opportunities in Switched Mode Power Supplies

Heinz van der Broeck
FH Köln - University of Applied Sciences Cologne, Betzdorfer Str. 2, 50679 Köln, Germany

Abstract The paper first describes different principles of switched mode power supplies (SMPS) by studying the power conversion stages of flat plasma display panels (PDP). It further investigates possibilities of integration in SMPS concerning semiconductors, reactive components and transformers. Finally, various application areas are presented and discussed. Moreover, it is shown that SMPS are not only used for supplying stabilised DC voltages but also for generation of special voltage and current waves to favourably run all kind of physical and chemical processes.

1 Introduction

With the beginning of this millennium computers, telecommunication and internet find growing interest in all areas of our society (industry, politics, media, press, public) and there is no doubt that the information technology (IT) is a main key for economic growth in the future.
However, the availability of energy and its quality is an important condition for any growth. In the public mind this aspect is sometimes neglected so that energy seems always available, just as a subject of trade and tax.
The generation and transport of energy, however, is a challenging task now and in the future. It can partly be solved by saving energy. Minimising the losses during transmission and conversion of electrical power presents one way of saving energy . This can be best realised by power electronics [1] which is a recognised technology for a large power range.
High efficient power conversion is not only important for large consumers but also for small ones if the number of devices is very high, which is the case for most electronic consumers. As an example the stand by mode of video recorders and computers can be mentioned where millions of systems are involved.
In the lower power range (up to 1kW) which also covers the power demand of most IT products, switched mode power supplies SMPS can be used for converting and conditioning electrical power efficiently [2].

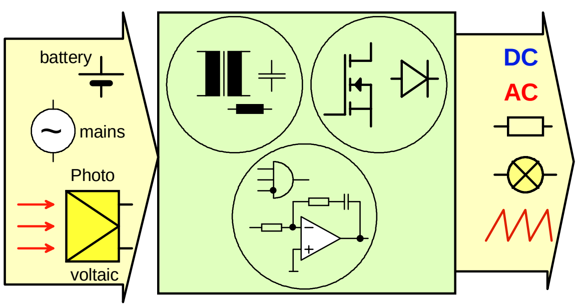


Figure 1 Switched mode power supply

Prof. Dr. H. van der Broeck is teaching "switched mode power supplies" at both, the FH Köln and the RWTH Aachen. He is a consultant of the power electronics group at the Philips Research Laboratories in Aachen

The main features of switched mode power supplies are high power density and high efficiency. Their application is thus always advisable whenever weight or losses have to be reduced or if miniaturisation is required.
Today, all kind of electronic consumer products already benefit from the employment of SMPS although it is not visible from outside. Indeed, in most electronic systems, SMPS operate as a hidden technology and they could also be favourably applied in many other products or applications.
This paper, thus, deals with principles of SMPS, their application areas and possibilities of their integration.

2 Introduction in SMPS

This chapter gives an introduction in switched mode power supplies "SMPS". Figure 1 shows components, power sources and loads of SMPS and it illustrates different conversion modes.
The centre of the picture represents the circuitry of a SMPS which is always composed by three groups of components:

- Power semiconductor devices
- Reactive components
- Control circuits.

Power Semiconductors are used as fast switches. They are either in the on-state where they carry high currents or in the off-state where they block high voltages. Due to an advanced semiconductor development and the use of special driver circuits, the voltage drop in the on-state is low, the leakage current in the off-state is negligible and the transient behaviour is very fast so that power semiconductors can be seen as ideal switches.
In switched mode power supplies Power MOS-FETs and fast diodes are applied. A standard MOS-FET is able to carry a current of 10A continuously and to block a voltage up to 500V. The typical turn-on and turn-off time of a transistor is less than 50ns and its conducting characteristic is that of a resistor (e.g Rdson = 0.2 Ω).

Reactive components are used for energy storage and direct converting of AC voltages and currents with galvanic isolation. Both, inductors and capacitors are used to store energy. While capacitors are bought as specified components, inductors and transformers have to be configured by designing suitable windings and by choosing a certain air-gap for a selected ferrite core.

Control circuits consists of both, analogue and digital components. They are used to close control loops, to provide certain protection functions and they have to generate the required pulse sequences for the power transistors. Although special uC and DSP have been developed for use in power electronics and SMPS, analogue control circuits still are very important due to cost and performance reasons.

SMPS are fed by DC or AC energy sources such as a battery, the single phase mains or by photovoltaic cells.
At the output SMPS provide constant DC voltages or currents, stabilised AC voltages or voltages and currents with special waveforms. In many cases the output has also to be galvanically isolated from the input. The way of power conversion depends on the application.
Stabilised and galvanic isolated DC voltages are needed to supply electronic circuits, e.g. in computer or telecom systems. Controlled currents are typically required for DC motor or other magnetic field applications.
Uninterrupptible power supplies provide low frequency 50/60Hz AC voltages generated by PWM-inverters.
Special DC or AC waveforms are needed to enable all kind of physical processes. Electronic ballast circuits for lighting and the deflection units for monitors and TV sets are examples which are produced in extreme high quantities.
In addition to the output behaviour, the input characteristic of SMPS is more and more important especially if supplied by the mains where power factor correction (PFC) is the desired feature. [3]

Apart from specifications of the power conversion some other aspects have to be considered in the SMPS design phase. For the final application certain standards have to be fulfilled for low and high frequency harmonics.
Moreover, the unit costs are always important due to strong competition on the global electronic market.

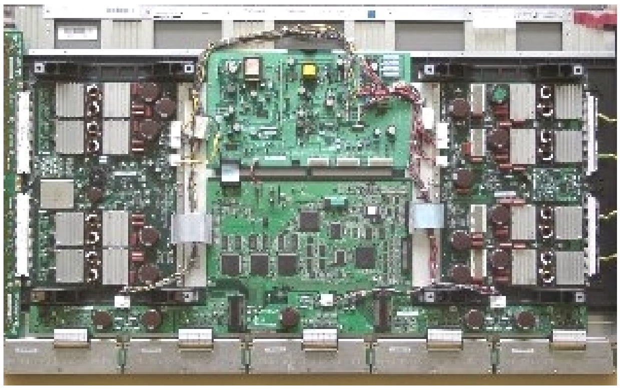
3 Principle operation of SMPS

In order to give a better understanding of the operation of a SMPS, an application example will be studied. Due to the present discussion on IT products, an advanced TV set with a large flat plasma-display panel (PDP) has been chosen [4].

Figure 2 42-inch plasma display panel PDP

New PDP TV sets provide sharp and clear pictures with bright colours at a large view angle [5]. They are already in use for high-end professional applications.

The plasma display panel is a very suitable carrier for explaining SMPS principles because of the different power conversion modes applied. Figure 2 shows a plasma display panel PDP with a 42 inch/106 cm screen while figure 3 presents the open back side of a 42 inch PDP unit.



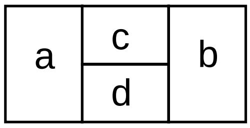


Figure 3 Back side view on an open 42-inch PDP. Assignment see left
Boards a,b,c are used for power conversion.

From the back view it becomes obvious that lots of electronics is required to run a plasma display panel although not all electronics is shown in figure 3. What may not be expected is, that most of the electronics is needed for power conversion. For instance the areas a, b and c of the panel backside are switched mode power supplies.
The plasma display TV is fed by the single phase mains (e.g. 220V-50Hz) and draws a power up to 800W from the line.

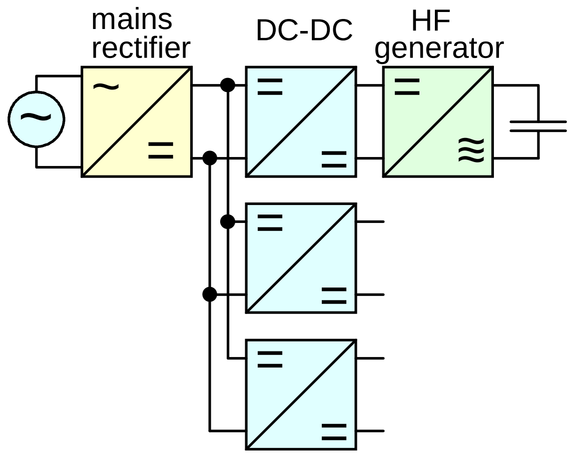


Figure 4 Power stages of the PDP electronic supply

As also illustrated in figure 4 the power for a PDP is converted by three different stages:

- mains rectifier,
- DC to DC converters
- high frequency generator.

Aim of the next chapters is not to explain special details of the circuits but to present the basic principles which are also used in other applications.

3.1 Mains rectifier

Mains rectifiers are used to convert the line AC voltage to DC. This can simply be realised by a diode bridge and an electrolytic capacitor.
The topology and their characteristic waves of the output voltage and the mains current are shown in fig. 5.

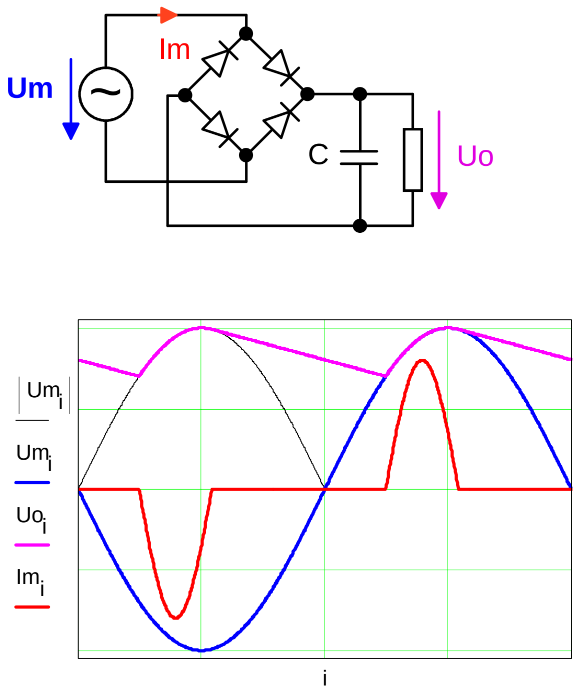


Figure 5 Standard mains rectifier with buffer capacitor (topology and performance)

It is evident that the amount of low frequency harmonics is very high which is a growing problem for the power utilities. Thus, certain standards have been set to reduce the low frequency harmonics in the mains [3].
For the power needed in a plasma TV set, the harmonics caused by a standard rectifier would not comply to the IEC555-2. Hence, the standard rectifier circuit has to be improved. It can be done by adding a boost converter, consisting of a transistor T, a diode D and a choke L.
The new topology presents a preconditioner. It is shown on top of figure 6.
Due to the decoupling choke L and the large capacitance C, the input voltage of the boost converter is given by

$$Ui(t) = \hat{U}m \cdot |\sin(2\pi \cdot f \cdot t)|$$

and the output voltage Uo is almost constant.
If the transistor is in the on-state the choke current iL(t) increases while it decreases in the off-state because of Uo > Ui. By controlling the on- and off-state times of the boost converter properly the current in the choke can be set sinusoidally in phase to the mains. This operation is also illustrated in figure 6.

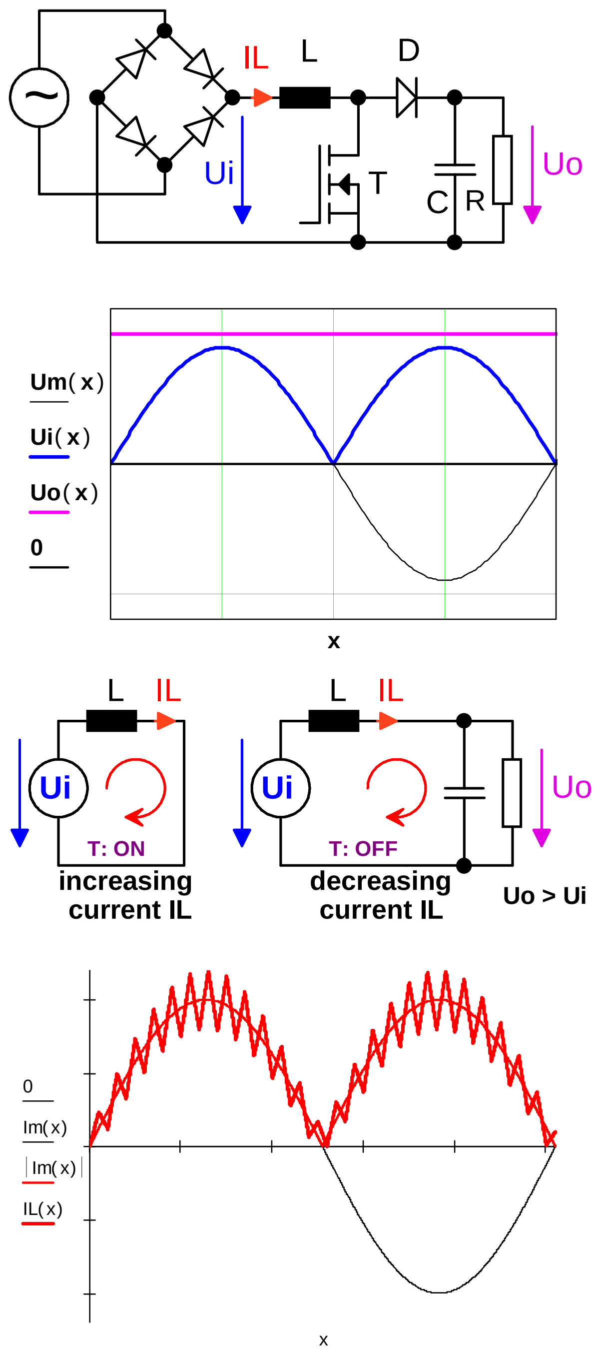


Figure 6 Preconditioner: topology, voltages, on- and Off-state, current in choke L and mains (HF filter is not shown in the topology)

Practically, high repetition frequencies are used and a small HF filter is inserted to keep the size of the choke L low and to avoid high frequency harmonics in the mains. The overall mains load, thus, shows a unity power factor. The amplitude of the current is set by an outer control loop which stabilises the output voltage to a value above the highest possible mains voltage (e.g. Uout=375V for 220V RMS AC).
Another advantage of the preconditioner is that it can also be fed by a lower mains voltage such as the 110V mains. It has, however, to be taken into account that the current is the limiting factor for the power conversion.

3.2 DC to DC conversion

DC to DC conversion is one of the most applied operation of SMPS. In general, an unregulated voltage (e.g. the rectified and smoothed mains) has to be converted to a stabilised, offset-free output DC voltage. The basic topology for this operation is the step down or buck converter which consists of a transistor T, a diode D, a choke L and a large output capacitor C. Figure 7 shows the buck converter and illustrates its operation for continuous current flow.

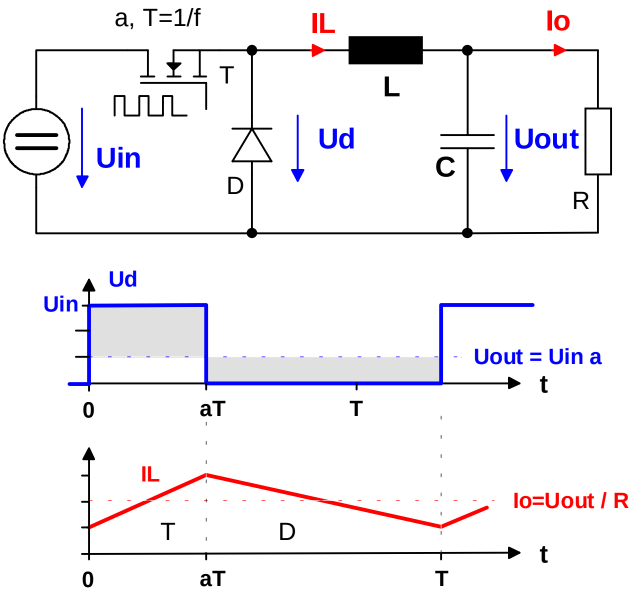


Figure 7 Step-down chopper (buck converter)

If the transistor T is in the on-state, the current iL in the choke increases linearly since Uin is greater than Uout. After the transistor is turned off, the current iL remains flowing but commutates to the freewheel diode D and decreases linearly due to the negative choke voltage: -Uout. The on- and off-states are set repetitively at a high frequency fs with the duty cycle a. The output voltage, which is equal to the averaged voltage at the diode D, can simply be stabilised by the duty cycle: $Uout = \overline{Ud} = Uin \cdot a$ (for continuous current flow) using a feed back closed loop control circuit.

In order to provide galvanic isolation and to allow larger voltage conversion ratios, a HF transformer has to be inserted. The basic operation remains almost unaffected $Uout = Uin \cdot a \cdot N2 / N1$.

However, the magnetisation current of the transformer has to be released via a feed back circuit consisting of a third winding N3 and a diode D3. The described "forward converter" is presented in figure 8.

Multiple output can be utilised by adding more secondary windings and post regulators (e.g. linear, chopper or a saturable choke technology). Another very often applied multiple output topology, which is preferable when low power or low cost are important, is the flyback converter[1]. Nowadays, LLC and LCC topologies are also considered for galvanic isolated DC to DC conversion.

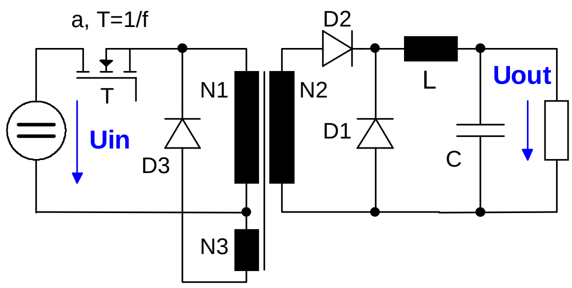


Figure 8 Forward converter

3.3 High frequency power generation

The operation of a plasma display panel requires AC voltages with a typical frequency of 200kHz and an amplitude of about +/- 170V. One condition for the ignition of the plasma is a fast transient between the positive and the negative voltage levels. This may be realised by using a transistor bridge which feeds the plasma cell via diagonal switching of the transistors. (see figure 9) Note, that apart from the ignition the plasma cell shows the characteristic of a capacitance Cp as depicted in the picture.

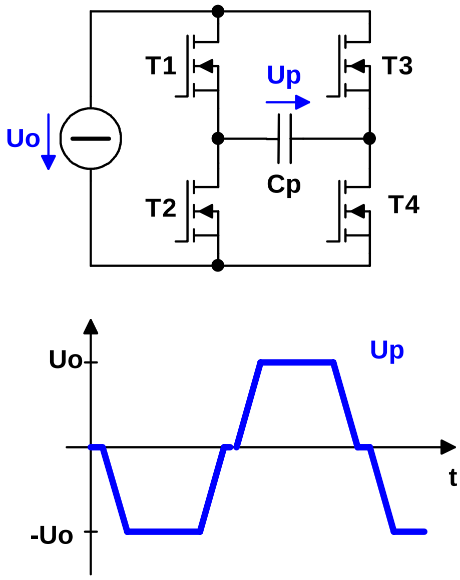


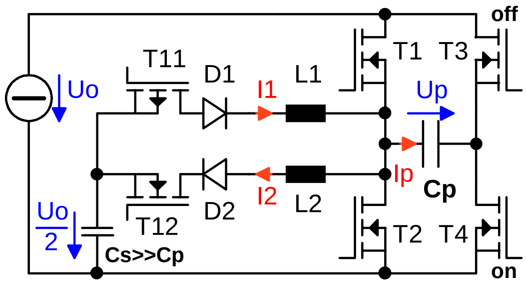
Figure 9 Basic PDP sustain driver circuit

If the capacitance Cp of the PDP is always charged and discharged via switches, high losses occur determined by the product of the averaged repetition frequency and the double energy stored in the capacitance. Moreover high current spikes occur by direct charging and discharging of the capacitance which causes electromagnetic interference problems EMI. Hence, the sustain-driver, which generates the required HF AC-voltage, has to be extended by an energy recovery circuit [6,7]. In general, this can be realised by resonant topologies, which consist of undamped LC circuits. In the PDP application the capacitance of the panel can be used as one component of the resonant circuit. The inductance has to be added as a discrete choke.

One possible resonant topology of a sustain-driver is shown in figure 10. It consists of a basic transistor bridge extended by a switched reactive network. For symmetrical reasons it is sufficient to study the resonant operation of one half-bridge. Hence, transistor T4 is assumed to conduct while transistor T1 and T2 alternately connect Cp to the positive or the negative rail of the DC supply Uo.

The recovery circuit for one half-bridge (T1&T2) consists of the transistors T11 and T12, the diodes D1 and D2, the chokes L1 and L2 and the auxiliary capacitor Cs. The capacitance Cs has to be large enough Cs>>Cp so that its voltage is almost constant Uc=Uo/2.

If T2 and T4 are in the on-state the panel voltage is zero: Up=0. In order to charge Cp, T2 has to be turned-off while T11 has to be turned-on. As a result a resonant circuit is formed by L1 and Cp, and the constant voltage at Cs generates a sinusoidal current i1(t). The current flow i1(t) stops automatically after half a period since the diode D1 prevents a negative current flow in L1. The current i1(t) charges the capacitance Cp and the resulting voltage Up oscillates from zero to the Uo. Once Up reaches Uo, transistor T1 can be turned-on at zero voltage and the ignition current can flow via the switches T1 and T4. In a similar way the voltage at Cp can also be commutated from Uo to zero. Here, transistor T12, diode D2 and choke L2 are involved. For T1 and T2 in the off-state, turning-on transistor T12 generates a sinusoidal current i2(t). It leads to a soft commutation of voltage Up from Uo to zero where transistor T2 can be turned on at zero voltage. The whole resonant operation of the resonant recovery circuit is illustrated in figure 10.



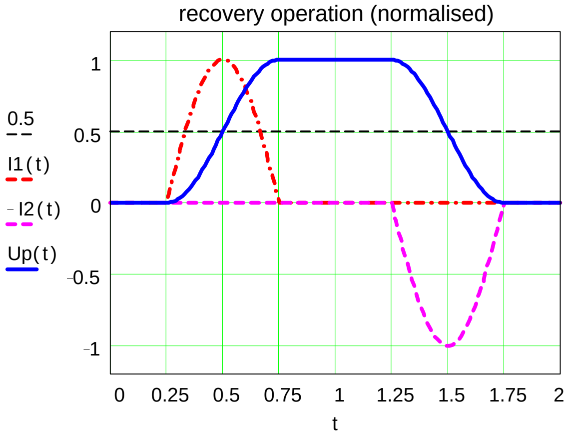


Figure 10 PDP sustain driver with energy recovery circuit (Note, only the recovery circuit for one half-bridge (T1&T2) is shown)

The energy stored in Cp is always taken from Cs and recovered to Cs which means that the circuit operates without losses principally. Furthermore, a sinusoidal current charges and discharges the capacitance so that the EMI level is kept low.

The resonant circuit presented here is a very good example for the integration of a SMPS in physical processes. The described sustain-driver presents an important part of the PDP electronics and its hardware is distributed on 2 large boards on the back of the panel. (see boards a and b in figure 3).

Note, that only the basic principle of the sustain driver has been explained here . In practice the sustain driver is more complex and other aspects have to be taken into account (e.g. supply of additional positive and negative voltages, consideration of the control electrodes, losses in semiconductors and chokes, parallel operation of subsystems, ...)

4 Integration in SMPS

Aim of any integration in SMPS is miniaturisation or cost reduction.

4.1 Integration of semiconductors

The first part of integration in SMPS is the control unit which presents a mixed analogue digital circuitry. Typically it requires an error amplifier, a pulse generator with settable frequency and duty cycle, driver stages for the lower and higher transistor, protection circuits (e.g. to avoid over-current) and auxiliary supplies. All these functions can be integrated in one chip and many different controllers are available for almost all established hard- and soft switching topologies today.

In another step the power semiconductors can be integrated as well to form a power IC. Although, it has been realised for certain applications it is not always the first choice due to the following reasons:

- Low voltage control circuits and HV power transistors are based on different technologies
- Less flexibility to chose transistors from different suppliers and at different power levels
- No large contribution to miniaturisation and cost reduction

4.2 Reactive Components in SMPS

In general, inductors, capacitors and transformers take the largest part of the SMPS size. Hence, any integration aiming at miniaturisation has to deal with these reactive components. As well known, the maximum energy to be stored in a capacitor or in an inductor is determined by its size assuming certain limiting parameters of the material involved (ferrite, ceramics, Emax, Bmax). Thus, the power density can be increased proportional to the repetition frequency: $P = W \cdot f$.

In the same way the power to be converted by a transformer depends on dimension properties, limiting material parameters and the repetition frequency:

$P = k \cdot B_{MAX} \cdot S_{MAX} \cdot A_{Fe} \cdot A_{Cu} \cdot f$.

Therefore, increasing the frequency is a first step for any miniaturisation in SMPS. However, the increase of the frequency is limited since it leads to higher switching losses and EMI problems caused by parasitic effects such as

- stray inductance of connectors
- leakage inductance of transformers
- parallel capacitance of MOS-FETs
- reverse recovery current of diodes

4.3 Resonant SMPS topologies

All basic SMPS topologies can be extended by reactive components to form resonant circuits which either operate with sinusoidal currents or sinusoidal voltages. If these circuits are only switched at zero current or zero voltage, switching losses are prevented and the EMI level is reduced. Resonant topologies are thus best suited for high frequency operation. A typical resonant operation has already been presented in chapter 3.3.

4.4 Using parasitics in resonant circuits

An overall optimisation of resonant SMPS topologies can be achieved by involving some of the parasitic effects mentioned earlier in the resonant operation, e.g. the leakage inductance of the transformer or the parallel capacitance of a MOS-FET.
The parasitic reactances to be integrated in the circuit depend on the selected topology and the operation mode. Many possibilities exist and are applied in various circuits today.

4.5 Manufacturing and Packaging

As far as high production quantities and low cost are an issue, manufacturing and packaging become very important and must be considered within the circuit design [8]. Moreover, manufacturing leads to reproducible parasitic reactances which may be favourably applied in the circuit. Optimised packaging is important for keeping the source of EMI low and for filtering the remaining part. Examples are:

- Use of potential fixed screens for reducing electric fields
- Minimising the area of connector loops for reducing magnetic fields [9]
- Avoiding the direct connection of heatsinks to switching parts of the circuit to reduce common mode noise (EMI)

4.6 Cooling and flat SMPS

Although SMPS principally operate without losses, losses occur due to nonideal components (e.g. voltage drops in semiconductors, resistances of connectors,..). These losses are dissipated in heat and flow via the surface of the SMPS to the ambient. The losses have to be limited according the allowable semiconductor temperature, the ambient temperature and the thermal resistance. A higher power density achieved by integration or miniaturisation thus requires a higher efficiency or a larger surface of the SMPS. The latter can best be realised by choosing flat constructions. The smaller the height the higher the surface to size ratio. In order to use available components a minimum height has to be kept for economy reasons.

A lot of the thoughts and design rules for optimising SMPS in size, performance and cost have been applied by several manufactures. Already more than 10 years ago one of these companies, the Vicor Corporation introduced a flat isolating DC to DC module based on a 1MHz quasi resonant forward topology. Vicor has improved its technology and packaging continuously and substantially improved performance and power density. [10]. Its latest generation provides an power density of 120W/inch³ (without a heatsink - to be added).

4.7 LCT integration

The previous sections have shown that an optimised SMPS with high power density can only be realised by a resonant topology to be operated at high frequency. Moreover, it has to be built in a flat or planar construction containing at least one inductance, one capacitance and a transformer (LCT). Consequently a further step of integration in SMPS is an integrated LCT (inductor, capacitor, transformer) [11] which is subject of an ongoing research [12].
In principle, an LCT module consists of alternating thin layers of conducting, isolating, dielectric and ferrite materials showing a similar terminal characteristics to that of lumped components.
Figure 11 illustrates the construction of an LCT module for a series resonant topology. The series capacitance C is formed by a dielectric layer D between the first P1 and the second P2 part of the primary winding. The series or leakage inductance Ls is created by the ferrite layer F between the primary P2 and the secondary winding S. In addition, a planar E-core is used.
Many other configurations can be considered applying this new integration method for reactive components.
For a successful product development of LCT modules many technology problems have to be solved which includes manufacturing, development of suitable thin ceramic layers, thermal management, bonding etc..

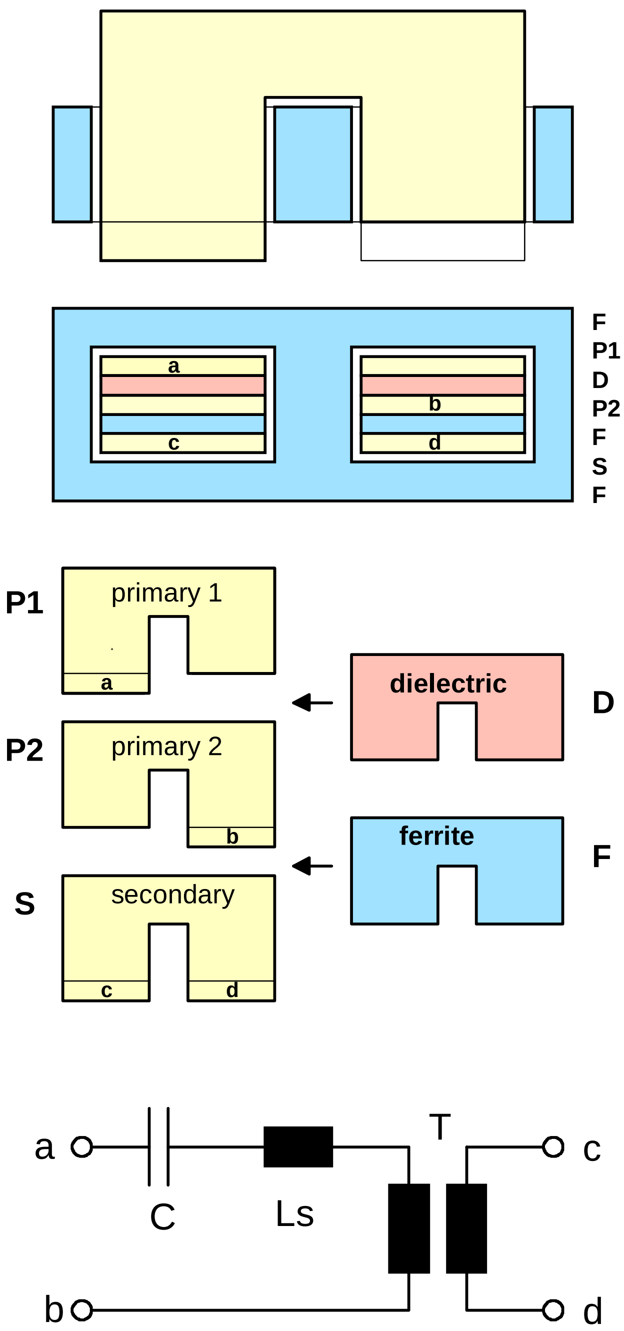


Figure 11 Principle of an LCT integration shown by the example of a series resonant topology

5 Application Opportunities for SMPS

Most SMPS are designed as DC to DC converters for supplying electronic circuits with stabilised DC output voltages. A typical application example is the computer supply where the required DC voltage is decreasing (e.g. from 5V to 2.5V) while higher currents are needed. The lower output voltage reduces the efficiency of the converter because of the voltage drop ΔU in the output rectifier: $\eta < U_{OUT} / (U_{OUT} + \Delta U)$. Assuming an output voltage of Uout=2.5V and schottky diodes with $\Delta U = 0.5V$ leads to an efficiency $\eta < 0.83$.

A reduction of the voltage drop ΔU can be obtained by synchronous rectifier [2,13], but an additional and more complex circuit has to be taken into account.
Hence, an optimised integration of power and control semiconductor is very promising in this application.

Another growing application of DC to DC converters can be found in the telecom sector where energy is provided from 48V battery systems.
In future new SMPS requirements in automotive applications may benefit from the development in the telecom sector as soon as cars are provided with a higher (42V) DC bus system [14,15].
These SMPS developments are specially challenging since apart from low cost a large temperature range and high mechanical stress have to be considered.

The growing use of electronics and stronger standards concerning mains interference leads to an increasing demand for power factor corrected PFC mains rectifier [3].This is not restricted to the single phase mains but also of interest for three phase lines.

Battery charging for portables (handy, laptop, shaver) is another important SMPS application where due to high volume power integrated circuits can favourably be implemented. There are already various products on the market.

Apart from classical DC to DC topologies, SMPS can also be designed to operate advanced physical or chemical processes. One example has already been shown in this paper (see PDP sustain-driver in 3.3) These applications are challenging when for instance an originally used large and expensive test equipment has to be replaced by a smart and small one.
Some more examples will be presented here which require different SMPS topologies.

Magnetorheological fluid (MRF) and Electrorheological fluid (ERF) change their rheological behaviour reversibly when exposed to a magnetic field or an electric field respectively. With an increasing field strength the fluid changes from free-flowing to linear viscous liquid and to semi-solid. Many new actuator applications are under discussion based on both, MRF and ERF technology (e.g. adjustable shock absorbers, forced feed back systems, pneumatic actuators,..) [16,17,18]. All these systems may benefit from small SMPS which have to provide either variable reactive current or high voltage pulses [19].

Another future application to be mentioned are piezoelectric transformers and actuators. These devices show a resonant characteristic with high quality factor. The resonant frequency typically lies between 50kHz and 150kHz. It has to be supplied accurately for a reliable operation. Different piezoelectric motors and actor principles are under discussion [20,21]. All of them require a power supply based on small and low cost SMPS topologies. An example of a resonant operating SMPS for a piezo-electric motor is given in [22].

6 Conclusion

It has been shown, that integration in SMPS is not only dealing with semiconductors but also with energy storage elements, transformers and the use of parasitic effects at high frequency. A SMPS topology has to be chosen depending on the application rather than on technology. Apart from standard DC voltage supplies for electronic circuits, SMPS can favourably be involved in all kind of physical and chemical processes. Hence, whenever the generation of special voltage and current waves or the power supply at small size and low cost is required within new applications or products, switched mode power supplies should be considered.

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