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Tenets of Switch Mode Power Supply Application Design

Vishwanath D Tigadi
Design Engineer Sankalp Semiconductor PVT LTD | Department Of Electrical Engineering IIT-Madras
Corresponding Author: Vishwanath D Tigadi

Abstract: *Modern day power converters have improved design, performance and efficiency at low design costs and production costs. This advantage comes along with complex control techniques, design methodologies and prudent application design. Power supply application design in the modern era has a clasp for better performance, low cost, better efficiency and minimal board areas. This paper discusses in detail about the key aspects of the process of Power supply application design of DC-DC converters, and behaviour modeling of exquisite features such as Duty cycle and frequency of operation; Challenges faced in the process of application design and behaviour modeling and their solutions.*

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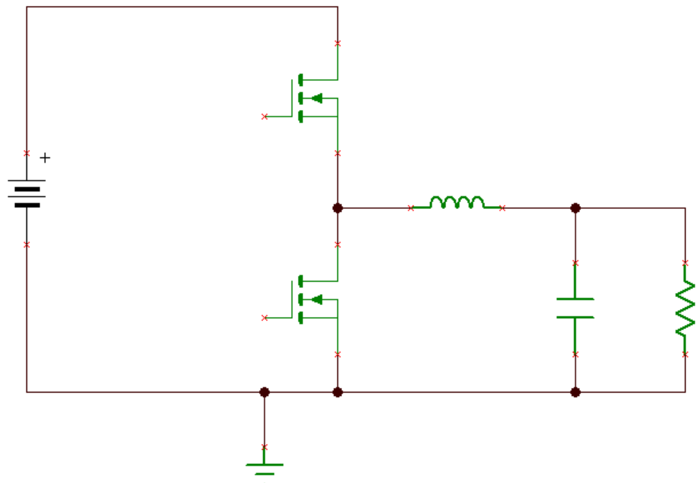
I. Introduction to switch mode power converters and application design

Switch mode power converters have revolutionized the electrical engineering since they arrived and have no signs of disappearing any time soon. Switch mode converters provide exceptional accuracy and control over output voltage, current and power delivered to the load. Switch mode power converters can be broadly classified into DC-DC converters, Inverters (DC-AC converters), Rectifiers (AC-DC converters) and AC Voltage controllers (amplitude and frequency).Invention and refining of power electronic switches such as BJT, MOSFET, SCR and IGBTs have made control of power supplies cheaper and faster. We now operate at switching frequencies of the order of 1~10 MHz, which was only a myth few decades ago.



Fig(1): Typical SMPS schematic (Buck converter power stage)

Application design is a deep rooted process in the electrical industry due to the inherent drawbacks of VLSI industry. Application design deals mostly on the level of PCB boards namely one level lower than that of system design and one level above the IC design and characterization. If we could have designed every element on to silicon, every power converter or an electrical system in general would typically look like a basic two port network with 3/4 pins. Application design is in market, also due to the design flexibilities that can be achieved on board cannot be achieved inside a chip.This paper takes a dive into DC-DC converters explain the phenomena, process and challenges of application design.However, Thelearnings can be extended to other power converters as well.

II. The four figures of merit of SMPS application design

Application design is a delicate process of balancing between the basic needs that a power supply must cater to the system. These figures of merit are namely speed, efficiency, cost and area. One or more of these features can be improved in a design only at the cost of other features. However, finding the right balance to meet the system specifications is the art of application design.

A. Speed

Modern day systems have very dynamic loading effects on power supplies and power supplies are always challenged with stability and transient overshoot, undershoot challenges. Modern day dynamics measure and comply with the transient changes of the order of 100ns to 1us. Older classical control systems have been replaced with modern nonlinear and hybrid control systems which have proven to be faster. Designing filters to accommodate these high speed demands is also a crucial part of application design.

B. Efficiency

Efficiency is yet another key feature of power supplies. An ideal power converter would have 100% efficiency delivering all the power from input to output without consuming any power in the process. But, in reality each element comes with its own power loss element. Sometimes these are necessary or inherent part of a device, sometimes they're mere parasitic power loss elements. The effective series resistances of passive components and turn on resistances of power switches are good example of these power loss elements. Efficiency in some cases can be improved by compromising on the cost and area of design. An application designer's duty is to get the best out of this bad bargain.

C. Cost

Cost, of all figures of merits, is the most valuable one in the competitive industry. It is always important to keep cost in check while aiming to improve other features. Although, some applications demand better performance over cost. Cost is also important from the sales and marketing perspective. It is important to make sure the functionality is preserved while optimizing cost of a power supply.

D. Area and volume

The Overall PCB area is a major concern for application design. With the shrinking infotainment devices which get thinner by the minute. Now a days power supplies for USB applications and such are built in less than 50 $mm^2$with high density of components. That is under a cm in length and breadth. However, the board area increases with complexity and control that a device possesses. The total height of component also plays a vital role in application design, slimmer TVs, Mobile Phones and other devices require shorter and shorter components. Once the BOM (bill of materials) is available, it is important to have a proper PCB designed. PCB design could be considered as a skill in itself, but plays a vital role in power supply application design.

III. The Through-hole and surface mount components

The Through-hole components are a particular set of devices which are manufactured with end leads that go through a hole drilled in the board and are soldered on the other face of the PCB. These are generally high current and high power devices. General through-hole components include diodes, Mosfets, Heat sinks, Zener diodes etc. These are indeed irreplaceable in some applications, but, consume huge amounts of the PCB in turn increasing the overall area.

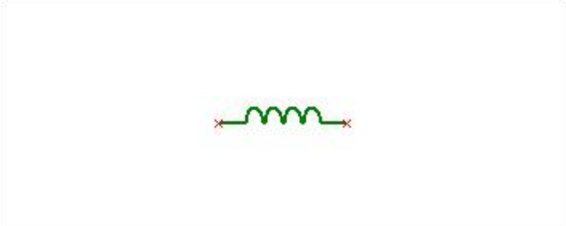
	
Through hole components	Surface mount components

Surface mount elements as the name suggest are surface dwellers. Surface mount elements are low power; low current rated small foot print elements which are soldered on to the surface of the PCB. These devices allow compact spacing, easy routing without interfering with other PCB layers. But these devices come in small packages as small as 0.6mm x 0.3mm. These elements are so small that sometimes it becomes difficult to solder them on to the board.

IV. The key components, their features and challenges that they bring to the table

A. Inductors

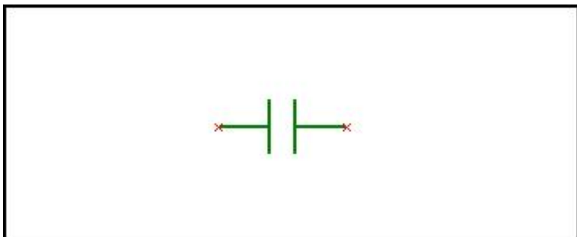
Inductors are the necessary evil of power supply design. These devices provide excellent filter properties with minimal DCR (Parasitic DC resistance). Inductors are criticized because of their humongous size. It was deemed impossible to fabricate on chip inductors for the major part of dawn of twenty first century. Recently few manufacturers have been able to embed inductors of the order of few μH into the IC package.

	
schematic Symbol	Real images

The main parameters of an inductor are inductance, DCR, DC current rating, saturation current rating and the physical dimensions foot print and height. It is axiomatic that one should look for the inductor calculated or slightly higher value to accommodate derating. It is recommended to select and inductor with low DCR, but over compensating on DCR may lead to increase in cost and total size. Every inductor has 2 current ratings DC current rating and saturation current rating. It is recommended that the lower of these two values should be greater than the maximum peak current that flows through the inductor. In case of soft saturation inductors, the saturation current rating could be ignored. Other parameters to be taken into account include tolerance, shielding and resonant frequency.

B. Capacitors

Capacitors are inseparable parts of power supply application design. This is mainly due to the fact that it is neither feasible nor realistic to build on chip capacitors. On chip capacitors are limited to the order of fF ~ pF. Any capacitors of the order of μF have to be connected on board and every pin of the Power supply ICs where constant voltage needs to be maintained demands a capacitor. Capacitors are also act as filter elements in switch mode power supplies. These capacitors are broadly classified into electrolytic and ceramic capacitors. It is important to make polarities a caution in case of electrolytic capacitors as they cannot withstand reverse voltages. Ceramic capacitors on the other hand are unpolarised. Ceramic capacitors have very low ESR (effective series resistance) and ESL (effective series inductance), but provide low range of capacitance. Electrolytic capacitors provide high range of capacitances but have significant ESR and ESL. It is always recommended to use a small ceramic capacitor in parallel with an electrolytic capacitor to reduce combined ESR and ESL due to parallel connection. There is a third set of capacitors namely polymer capacitors. These capacitors barely find their way in power supply application design due to their large size. They have a moderate ESR and can withstand only unidirectional voltages. Apart from ceramic, aluminium electrolytic and Tantalum types, capacitors also available in film, thin film, aluminium polymer, mica, Tantalum polymer types.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The main parameters of a capacitor are capacitance, ESR, Voltage rating and the RMS current rating. Alongside these parameters, there are foot print, thermal ratings, etc. It is always recommended to have a larger VDC rating or higher capacitance or both in case of ceramic capacitors. These are subject to voltage derating. Other major parameters are tolerance, height and mount type.

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C. Resistors

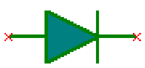
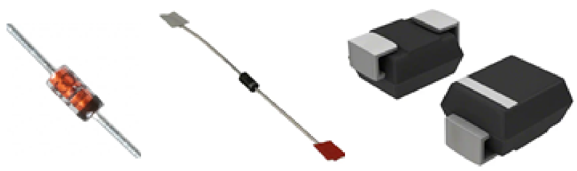
Resistors are fundamental electrical elements, however it is difficult to fabricate large resistors inside the IC, hence most of them are connected on the PCB. Resistors are mainly used for biasing and sensing circuits. They also find their places in few oscillators and other special features in case of switch mode power converters.

	
schematic Symbol	Real images

The main parameters of a resistor are resistance rating, tolerance and power rating. In some high voltage applications voltage rating also is taken into account. Foot print is also important to conserve board size, but it increases with power rating of the resistance.

D. Diodes

Diodes are used in switch mode power converters as uncontrolled switches which conduct forward current when reverse biased. The advantages of having a diode for secondary switch in a SMPS is that, we do not have to bother about reverse currents, and building a driver circuit for secondary switch, and also cross conduction between supply and ground. However this comes at the cost of efficiency. And unlike power Mosfets, it is difficult to fabricate these large diodes on chip and have to be connected externally on PCB.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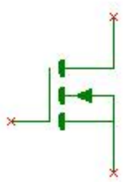
The main parameters of a diode to be considered are VRRM (Reverse repetitive voltage magnitude), IDC rating, the peak current rating, and the type. It is often suggested to use low Vf fast switching diodes in power supply applications to reduce power dissipation. Foot print, height, and reverse recovery time, reverse leakage current and thermal resistance are other parameters to be taken into account for efficient design.

E. Mosfets

Mosfets are irreplaceable parts of modern SMPS systems. They're the most reliable controlled switches with great efficiency. Mosfets are generally integrated in to the IC for low power and low voltage power converters. However, in high power and high voltage power converters the Mosfet size required becomes so enormous that it is no longer feasible to integrate them into the chip. Also, in some low power and low voltage converters, external Mosfets are supported to give the application designer flexibility over design and topology selection i.e., a single controller can be implemented into different topologies such as buck, inverting buck boost etc.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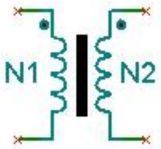
The main parameters of a mosfet that need to be considered are channel type, enhancement mode, IDC rating, VDS rating, VGS rating, Vth rating, junction to ambient thermal resistance and the maximum temperature allowed. It is important to take the temperature safety measures as power Fets are subject to excessive heating. Heat sinks could be used to increase thermal effectivity, at the cost of board size. Power losses and increase in temperature in the Fets depends on several factors such as Ron, rise time, fall time, gate charge etc. it is important to bring these characteristics into play during selection to optimize the designs. Footprint and height are the other major parameter to be taken into account for efficient design.

F. Transformers

Transformers are an exquisite part of power supply application design especially in DC-DC converters. The transformers are used only in those supplies where isolation is needed. These transformers, like inductors are huge in size and acquire a large board space. Transformers are generally available in fixed inductances and turns ratios by several manufacturers, but in special cases they can be custom made using core bobbin assemblies. This requires separate expertise in transformer design as the process is slightly sophisticated.

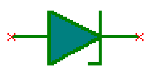


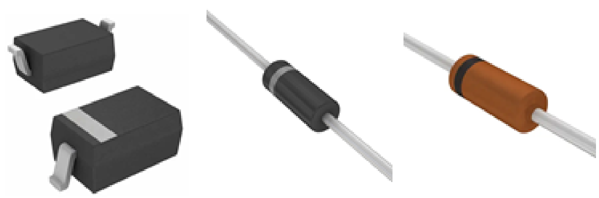
schematic Symbol	Real images

The main parameters of the transformer to be considered during selection are the inductance of primary and secondary windings, the turns' ratio and the leakage inductance. One must also take the parasitic resistances of windings to account for power losses. Foot print is yet another parameter to be taken into account for efficient design.

G. Zener diodes

Zener diodes are poor man's voltage references. These act as voltage regulators when reverse biased. However, this is not recommended for high current applications, where Zener diode draws amperes of current. Zener diodes can be used as voltage limiters in several cases as well where the gates of few Fets need to be clipped at some limit.



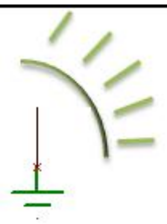
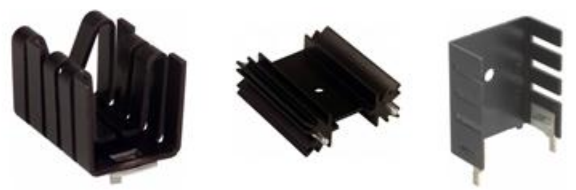


schematic Symbol	Real images

The main parameters to be considered during Zener diode selection are the Zener voltage and the power rating of the Zener diode. There are other parameters such as tolerance and maximum impedance that also need to be considered depending on the application. Foot print is yet another parameter to be taken into account for efficient design.

H. Heat sinks

Heat sinks are used only when a particular heat power loss element is unable to dissipate all the excessive heat effectively. These elements are mainly ICs, Mosfets and diodes. The power dissipation occurs predominantly in power path elements which are traceable in the path between Vin and Vout. This excessive heat may burn the device from the inside or force shutdown if thermal protection is present. This is where heatsinks come into play. It is always recommended to avoid heat sinks if possible by replacing the high losselements with efficient ones if possible due to large size of heatsinks.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The main parameters of heatsinks are surface to ambient thermal resistance, material, foot print and height. The other parameters such as maximum power rating are also important if the power that needs to be dissipated by the heatsinks is enormous. It is also important to make sure heatsink and its corresponding power loss element is geometrically compatible.

V. Worked Example

Asynchronous buck converter power stagedesign for continuous conduction mode.

Parameter	Value	Units
Vin	3.3	V
Vout	2.5	V
Iout	1	A
IL_pkpk	0.3	A
Vout_pkpk	0.025	V
Fsw	700	kHz

Table(1) Design constraints

$$\mathbf{D = \frac{Vo}{Vin} = \frac{2.5}{3.3} = 0.7576}$$

$$\mathbf{Il_{pk} = 1.3A}$$

$$\mathbf{L = \frac{Vin - Vo}{I_{Lpkpk}} * D * Tsw = 2.88uH}$$

$$\mathbf{Co = \frac{1 - D}{8 * L * FSW^2 * \left(\frac{\Delta V0}{V0}\right)} = 17.14uF}$$

Parameters calculated:

Parameter	Value	Calculated / Measured
D	0.757575758	Calculated
L	3.20667E-07 H	Calculated
Irms	1.267872233 A	Calculated
DCR	220mΩ	Measured
Cin	1.59008E-06 F	Calculated
Icin_rms	0.802422583 A	Calculated
ESRin	0.004 mΩ	Measured
VCin	3.3 V	Measured
Cout	3.57143E-06 F	Calculated
ICout_rms	0.779422863 A	Calculated
ESRout	0.004 mΩ	Measured
VCout	2.5 V	Measured
Vds_M1	3.3 V	Measured
Vgs_M1	3.3 V	Measured
Ron_Q1	7.5mΩ	Measured
Im1_rms	1.103541132 A	Calculated
D1 Vf	0.35 V	Measured
D1 IDC	1.3 A	Calculated
D1 VRRM	2.5 V	Calculated

Table (2) Design values

Bill of materials

Component	Part number	Discription
L	744028003	3.3uH , 30% , 1A, 0.22Ohm, shielded, 85MHz, surface mount, 0.11"X0.11"X0.047"
Cin	C0603C106M9PACTU	10uF. 6.3V, 20%, X5R, surface mount, 0.063"X0.031"X0.035"
Cout	C0603C106M9PACTU	10uF. 6.3V, 20%, X5R, surface mount, 0.063"X0.031"X0.035"
D1	MBRA210LT3G	10V, 2A, 0.35V, 700uA, schottky, surface mount, DO-214AC, SMA
M1	FDS6570A	N-channel, 20V, 8V, 15A, 7.5mOhm, 4700pF, 66nC, 2.5W, surface mount 8-SOIC

Table (3) BOM

VI. Conclusion and future scope

The main components of power supply application design namely capacitors, inductors, resistors, diodes, Mosfets, Zener diodes and heat sinks have been explained in detail. Parameters governing the selection of each power supply element have been dealt in great detail. A worked example on power supply application design has been demonstrated. The future scope lies in extending the study to AC-DC converters such as PFC boost and PFC Flyback converters where AC related challenges such as PF (power factor) and harmonics can be studied in detail.

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