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Power Losses in Switch Mode Power Converters

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Abstract: *Switch mode power converters are inseparable parts of modern electronic world. Their applications range from infotainment gadgets to modern militaristic systems. They have wide range of topologies and architectures. And, permutations of these topologies and architectures yield hundreds of unique power converters with well-designed features such as speed, Efficiency, size and cost. Efficiency among the listed features stands out a major need in power and battery management systems. This paper explains the power loss elements of switch mode power converters and power losses in these elements in detail at intuitive level. These concepts can be further extended to study any architecture or topology of switch mode power converters.*

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I. Introduction

Power switches and their types

Power switches are the elements that are designed to control the flow if power/energy in the circuit. In other words, they can make or break an electrical circuit. Every electrical and electronics application uses at least one switch to perform ON and OFF operation of the device. In electrical engineering an ideal switch is expected to block voltage is both directions when off and allow current in both directions when on. But, most of the electrically controlled switches have the inherent drawbacks such as incapability to block voltage in either directions; or, the incapability to conduct current in both directions and as such. Based on the method of control these switches are classified into different categories such as mechanical switches, electrically controlled switches, float switches etc., each of these witches are application bound. In power electronics we are bound to electrically controlled switches. This is mainly due to need for high frequency switching.

Switches can be further classified into different types based on several factors such as:

i. Method of action (Manual and Automatic)
ii. Number of contacts (Single contact and multi-contact)
iii. Number of poles and Throws(SPST, SPDT, DPST, etc.,)
iv. Construction (Push button, Joystick, etc.)
v. Based on state (memory and locked switches)

Semiconductor devices as power switches

Electric switches are commonly known as solid state devices due to absence of moving parts. Most of the electronic and electrical applications are controlled by semiconductors. These devices range from digital inverters of the size of few square nano meters to entire power system including motor control, street lights etc.

Diode

A diode is a 2 terminal second quadrant operating, voltage controlled switch. A diode in general is capable of blocking a reverse bias voltage and capable of conducting current in forward bias conditions. These devises are best used as rectifiers when designed to have low forward drop. Semiconductor materials such as Silicon and Germanium are used to build the power diodes. Modern construction techniques have given rise to diodes with lower power dissipation and fast switching. Schottky diode and ultrafast diode are few examples of such diodes.

BJT

A BJT can be defined as a current controlled switch. IT's collector current is a function of base current. It is capable of blocking both forward and reverse voltages when off; and capable of conducting unidirectional current. Hence it operates in first and second quadrants of V-I Characteristic graph, BJTs are of two types NPN and PNP. Both act as closed switch when a small base current is injected and open switch when base current is cut.

MOSFET

MOSFETs are unipolar high frequency switching devices. More than 98% of SMPS use Fets as switching elements. These devices are generally represented as voltage controlled switches as the gate terminal of a FET doesn't draw any current. These also operate in first and second quadrants of V-I Characteristic graph. Mosfets are of two types as well. P-type and N-type. These are complimentary switches and are commonly used at places where SPDT electrically controlled switches are required.
Preceding further this paper will discuss power losses in Mosfets in detail.

Block diagram of Switch mode power converters

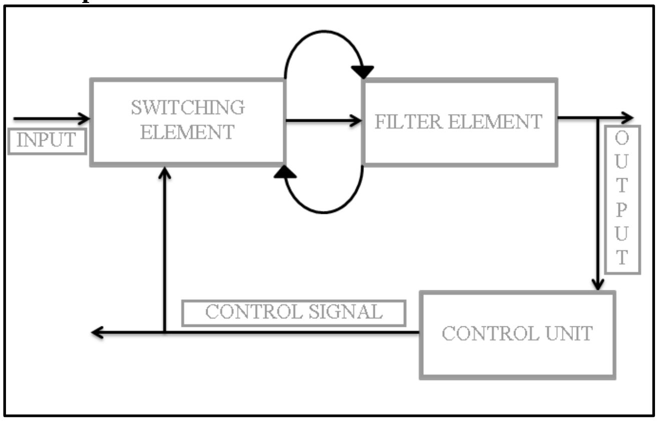


Fig (1): General structure of a switch mode power converter

The above figure shows the basic elemental representation of a switch mode power converter. By changing the arrangement of switching and filter elements different topologies of SMPS can be arrived at. Each of these topologies have their own unique input to output relations and can be exploited according to the needs of the load demands and the designer.

Significance of RMS values

In order to determine the efficiency of a system it is rudimentary to understand the power loss in each of its elements and the power delivered to the load. Power calculations in general are done under steady state and the calculated power is the average power dissipation. However, the calculations get distorted with average quantities of voltages and currents. Hence we use RMS values of the quantities involved to estimate the power loss in a system.

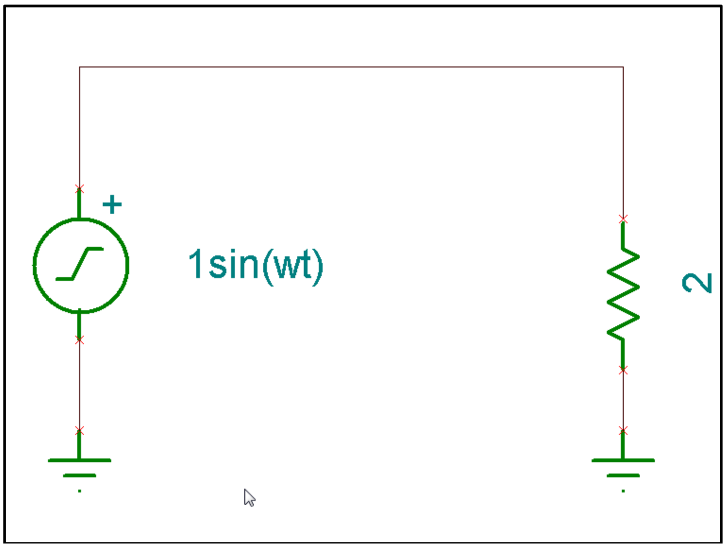
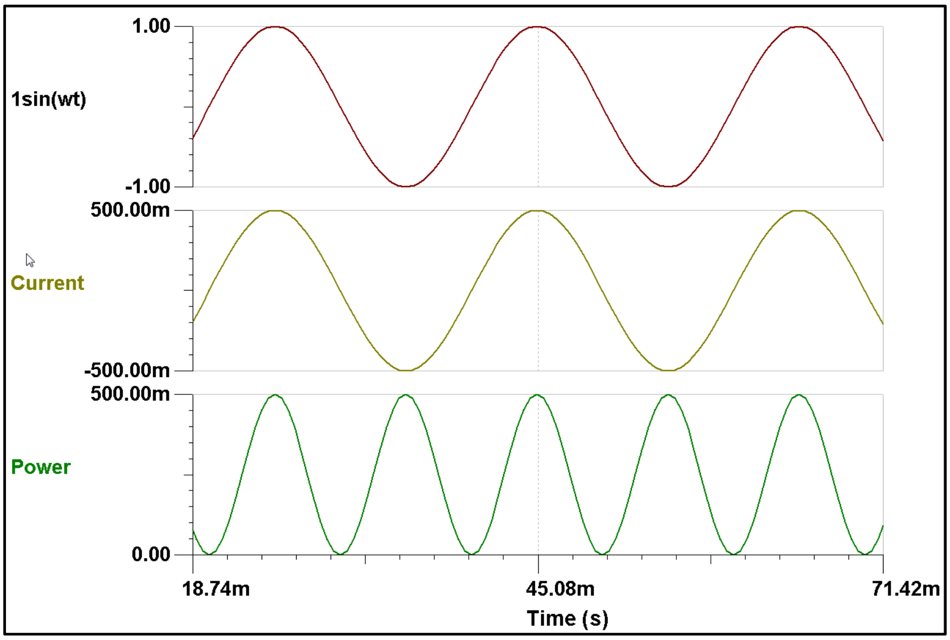


Fig (2): Voltage V = 1 sin (ωt) applied across a resistor of value 2 Ω

Consider a Voltage V = 1 sin (ωt) applied across a resistor of value 2 Ω as shown below. The average voltage across 2 Ω resistor over one AC cycle is zero and similarly the average current through 2 Ω resistor over one AC cycle is zero. But, the average power dissipated over one switching cycle is not Zero.

$P = V_{AVG} * I_{AVG} = 0$: This is a wrong approach to calculate average power dissipation.



Fig(3) : Voltage current and power dissipation waveforms

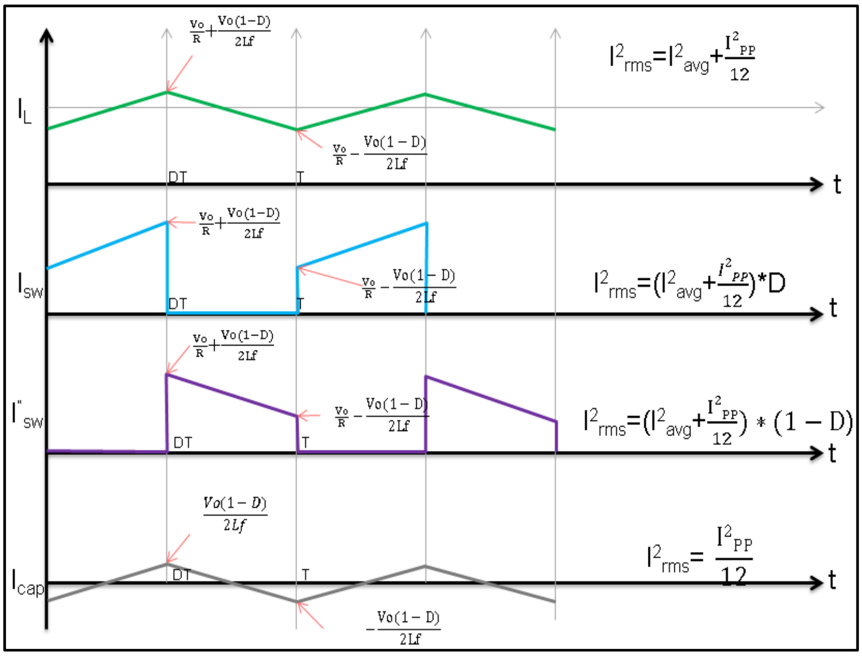
$$P = \int V * I = \int 1\mathrm{Sin}(wt) * 0.5 * \mathrm{Sin}(wt) = \frac{1}{2\sqrt{2}} = \frac{V}{\sqrt{2}} * \frac{I}{\sqrt{2}} = V_{RMS} * I_{RMS}$$

The equation above is a realistic interpretation of power loss in the resistor. Hence, we use RMS quantities to interpret average power consumption/dissipation in any element.

Conduction losses

Conduction losses are the losses that dissipate power in on-state of the non-ideal switch (Fig1). Any realistic switch either mechanical or semiconductor, will have an on state resistance of few mΩ in practice. The power dissipated in this switch is given by the equation below.

$$P_{Conduction} = I_{RMS}{}^{2} * Ron$$



Fig(4): General Waveforms for conduction losses

Switching Losses

It is often misunderstood that switching losses are driver losses. But, one should note that switching losses in a SMPS is nothing but the additional conduction losses that occur forcefully before the switch is fully turned on or off. The below graph shows the curve where IDS starts flowing and saturates to maximum value even before VDS has settled to ID*RDS (ON). This causes an additional loss as shown in the following graph of Psw.

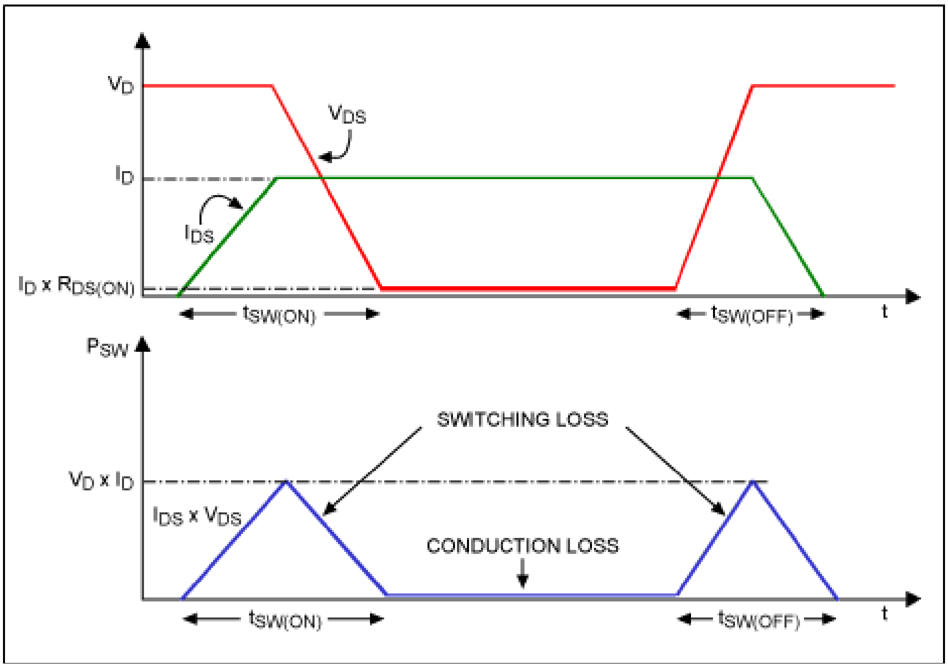


Fig (4): Switching losses timing diagram

Switching losses in a power switch is given by the below equation.

$$P_{SW} = \frac{V_D * I_D * \left(t_{SW}(ON) + t_{SW}(OFF)\right) * FSW}{2}$$

Coss Losses

Coss capacitor is the effective sum of CGD and GDS of a Mosfet. The Coss capacitor charges from zero to the VDS voltage of the mosfet and discharges back to zero every switching cycle. The Coss capacitor losses can be ignored for high power applications as Coss is often of the order of fF to nF. However for Low power applications Coss loss becomes significant and is given by the equation below.

$$P_{Coss} = 0.5 * Coss * VDS^2 * FSW$$

Gate Driver Losses

During Every switching cycle, gate capacitor has to charge for zero to Driver Voltage and then discharge to zero again. This charging and discharging occurs through the pull up and pull down resistors of the driver circuit. During turn on the gate capacitor is charged to Qg (Maximum gate charge) of a mosfet and during turn off the same capacitor is discharged from charge Qg to zero. Thus effective gate driver loss is given by the equation below.

$$P_{Driver} = (R_{pullup} + R_{pulldown}) * Qg * V_{driver} * FSW$$

Body diode losses

In case of synchronous power converters working in continuous conduction mode, it is taken care that there is some time lapse between one switch turning off and other switch turning on. This is done to make sure there is no short circuit formation from supply to ground. These small instances of time are called 'dead time'. During this dead time, the body diode of the switch that is connected to ground will conduct the inductor current. And the power loss that occurs during this dead time is called body diode loss.

$$P_{body} = (I_{L_{peak}} + I_{L_{valley}}) * Vf_{body} * T_{dead} * FSW$$

Inductor and Capacitor losses

Inductors and capacitors are in general energy storing elements. However, in practical situations the inductors and capacitors come with parasitic resistances called DCR and ESR for inductor and capacitor respectively. These resistances consume additional power given by the following equation.

$$P_{\mathrm{Conduction}} = I_{\mathrm{RMS}}{}^{2} * R_{\mathrm{ESR}/\mathrm{DCR}}$$

Power diode losses

In case of the asynchronous power converters, the secondary controlled switches are replaced by uncontrolled switches namely diodes. These diodes are forward biased and conduct a forward current of IDC (generally Iout of the SMPS). This results in forward current losses in power diodes. There are other power losses in a diode known as reverse recovery losses. These losses are encountered on if simple PN junction diodes are used. These losses are overcome by employing special diodes such as Schottky diodes and ultrafast diodes.

$$P_{\mathrm{diode}} = I_{\mathrm{DC}} * \mathrm{Vf}$$

Zener diode losses

Zener diodes are generally used as voltage regulators in SMPS circuits. These find their application at output node, bias node and in snubber applications. The very purpose of adding Zener diodes is maintain constant voltage in reverse bias and this does not have any regulation over the current flowing. The power loss in the Zener diode is often of the order of 10-3 watts. And the current flowing will be unidirectional and the average value is taken for power calculations.

$$P_{\mathrm{ZENER}} = I_{\mathrm{DC}} * V_{\mathrm{ZENER}}$$

Transformer losses

Transformers are part of special topologies of SMPS namely Fly-buck, Fly-back, Half Bridge, Full Bridge and push pull converters and few others. These are used to provide electrical isolation between input and output. The major difference between a Flyback transformer and main or audio transformers is that Flybacks transfer as well as store energy, but only for a just a fraction of an entire switching period. The secret behind that is the coil winding on a ferrite core that has an air gap; it increases the magnetic circuit reluctance for storing the energy. These transformers are specially constructed to topology specific applications.

The conduction losses in the transformers are decided by the parasitic resistances of the windings and the RMS currents; While the core losses depend on a wide number of parameters such as core material, core geometry, air gap etc. for all practical purposes, it is acceptable to assume core losses equal to conduction losses. The total transformer losses are given by the equation below.

$$P_{\mathrm{transformer}} = 2\left(I_{\mathrm{Pri}\,\mathrm{RMS}} * R_{\mathrm{pri}} + I_{\mathrm{sec}\,\mathrm{RMS}} * R_{\mathrm{Sec}}\right)$$

Quiescent current losses

Any Integrated circuit will have internal error amplifiers, comparators and other functional elements that need to be biased in order for the system to function as expected. These devices draw a constant amount of current. This is called quiescent current and is drawn from the bias supply. Sometimes this bias is drawn from the input of the power converter and in some high voltage applications this is drawn from the output side. However the power dissipated remains the same.

$$P_{\mathrm{Q}} = I_{\mathrm{Q}} * V_{\mathrm{BIAS}}$$

Other losses and their (in)-significance

Other Circuit elements such as Compensation capacitors and resistors, soft start capacitors, the shutdown circuit, the current limit sensors, bias pin capacitors etc., will have a significant start up time power dissipation. However, under steady state these elements do not dissipate accountable amount of power. Generally the power dissipated by these elements will sum up to the order of few hundred nano-watts. Hence the power losses in these elements are ignored; and it is a good approximation to do so.

Efficiency

Efficiency of an electrical system is the ratio of power delivered to the power received. This is also equivalently represented by ratio of output power to the sum of output power and total losses. The equations for efficiency are given below. It is a commonly used convention to represent efficiency in the form of percentage. Systems are categorized based on efficiency and SMPS prove to be good merchants of efficiency ranging from 70% to 98% in general applications.

$$\text{Efficincy}(\eta) = \frac{\text{Pout}}{\text{Pin}} = \frac{\text{Pout}}{\text{Pout} + \text{Total Losses}}$$

II. Conclusion

The prerequisites to efficiency and power loss calculation have been discussed. Power loss calculation for general SMPS devises has been discussed. Detail study of power loss in linear and nonlinear elements such as inductor, capacitor, power Fets and transformers has been covered. The methodology discussed can be extended to any topology of switch mode converters and to any control architecture. A detailed view on need for efficiency calculations has been represented.

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