Power Electronics Education Electronic Book

Welcome to PEEEB

Lecture 2: Power Switches

Presenter: Dr. Firuz Zare

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Contents:

1. Ideal and Practical Switches
2. Losses, Harmonics and EMI
3. Types of Switches
4. Gate Drives
5. Power Switches in Different Applications

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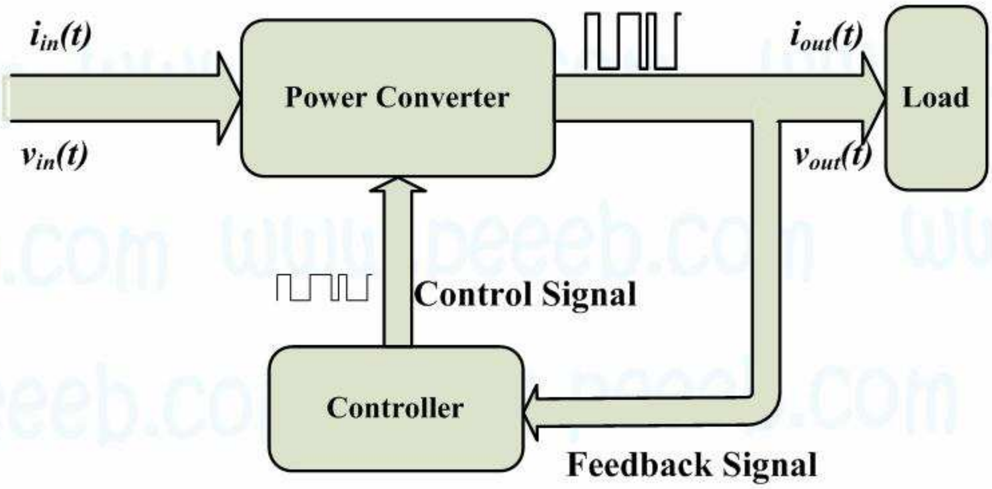
Ideal and Practical Switches

Key elements in a power converter are power switches which operate at high voltage and/or current. They chop DC or AC voltage/current based on a pulse pattern generated by a controller to achieve a desired voltage/current.



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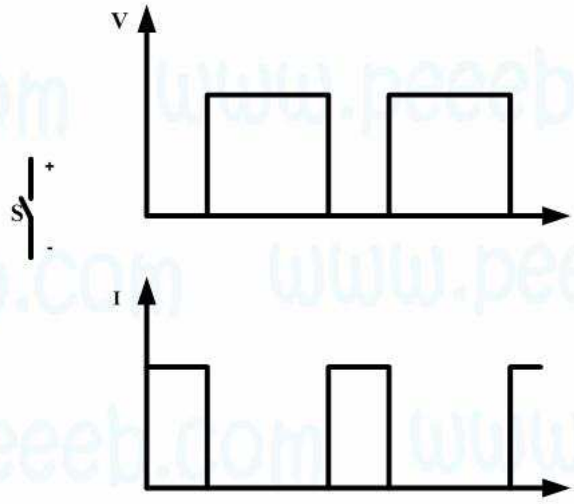
Ideal and Practical Switches

When we consider a power switch as an ideal switch, that means the switch can handle unlimited current and blocks unlimited voltage.

The voltage drop across the switch and leakage current through the switch are zero.

The switch is turned on and off with no rise and fall times.

This assumption helps us to analyze a power circuit but for design and practical considerations we should consider real power switches!



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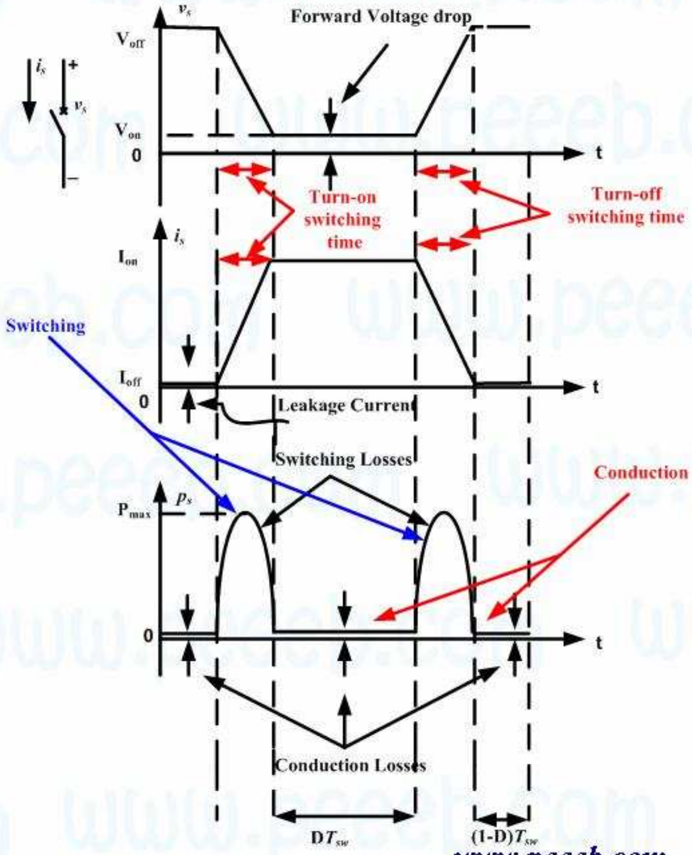
Ideal and Practical Switches

In a real case, ideal switches do not exist. During switching transients, there are significant switching losses associated with dv/dt and di/dt. These phenomena depend on several issues such characteristics of power switches, control signals, gate drives, stray parameters and operating points of the system.



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Ideal and Practical Switches

Real power components have limited power, voltage and current-handling capabilities.
They also have limited switching speed due to charging and discharging internal capacitors existing between the junctions which limit the maximum operating frequency of the device and create switching losses.
On-state and *off*-state resistances or voltage drop and leakage current create conduction losses.

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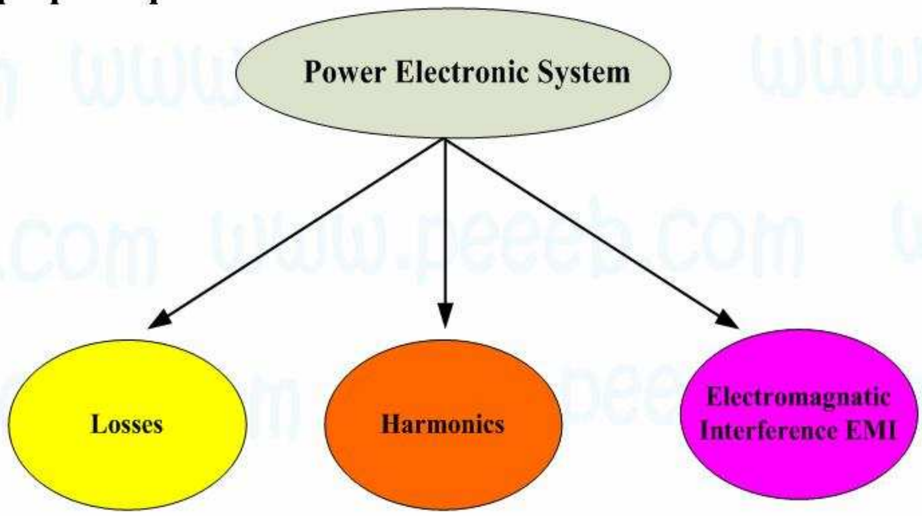
Losses, Harmonics and EMI

Three major issues to design a power electronic system are Losses, Harmonics and Electromagnetic Interferences (EMI). These issues affect system cost, size, efficiency and quality and it is a trade-off between these factors.

It is very important to know these issues at the early stage of a design and select appropriate power switches.



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Losses, Harmonics and EMI

Losses:

There are different types of losses in a power converter such as:

- **Conduction and switching losses in power switches**
- **Losses in a controller**
- **Losses due to charging and discharging stray inductances in a power converter**

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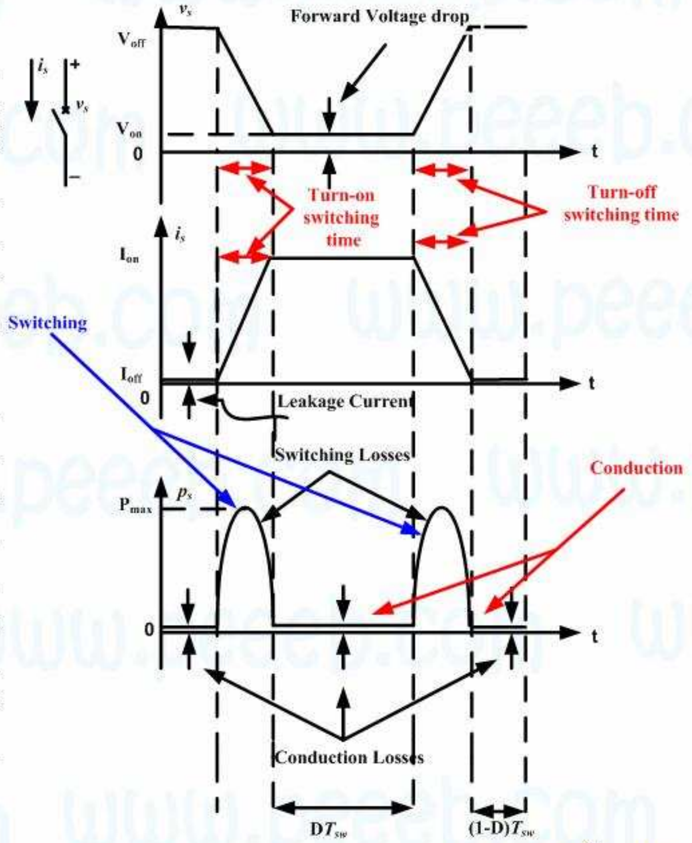
Losses, Harmonics and EMI

When a switch is turned on or off, energy is lost during the switching transients when operating points of the switch are changed from on (off) to off (on) states through an active state. This type of energy loss is called switching loss of the power switch.

When a switch is off, normally a leakage current through the switch is very small and we ignore the energy loss associated with off-state. But when the switch is on, the energy loss depends on current through the switch and forward voltage of the switch. This type of energy loss is called conduction loss of the switch.



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Losses, Harmonics and EMI

The average power loss in a switch over one switching cycle is given by the following equation which consists of the conduction and switching losses:

$$\overline{P}_s = \frac{1}{T_{sw}} \int_0^{T_s} i_s v_s dt = \overline{P}_{cond} + \overline{P}_{sw}$$

Assuming that the on and off switching times are small compared to switching cycle, T_{sw}, and the leakage current is negligible, $I_{off}=0$. Thus the conduction loss is given by:

$$\overline{P}_{cond} = V_{on} \times I_{on} \times \frac{t_{on}}{T_{sw}}$$

Where t_{on} is the time when the switch is in on-state, V_{on} is a voltage drop across the switch and I_{on} is a current through the switch assuming it is constant in magnitude. We can define a duty cycle (D) as a turn-on ratio with respect to switching cycle, T_{sw}.

$$D = \frac{t_{on}}{T_{sw}}$$

Thus, $\overline{P}_{cond} = V_{on} \times I_{on} \times D$

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Losses, Harmonics and EMI

The switching loss should be calculated based on instantaneous current and voltage waveforms. Normally we approximate the waveforms to be able to find the switching losses. High bandwidth measurement circuits with low stray inductance are required to measure the voltage and current waveforms accurately which are very challenging.

$$\overline{P}_{sw} = \frac{1}{T_{sw}}\left(\int_{t_1}^{t_1+t_{sw\_on}} i_s v_s dt + \int_{t_2}^{t_2+t_{sw\_off}} i_s v_s dt\right)$$

Where, t_1 and t_2 are the times when gate signals are applied to turn on and off the switch, respectively, t_{on} and t_{off} are turn-on and turn-off switching times.

Losses, Harmonics and EMI

This equation shows that the switching loss is proportional to the switching frequency .

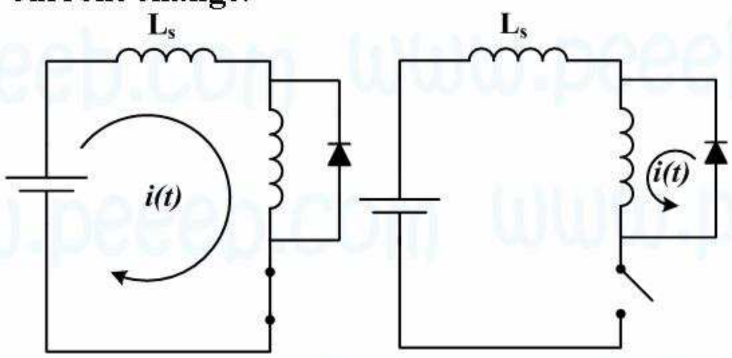
$$f_{sw} = \frac{1}{T_{sw}}$$

Thus increasing the switching frequency increases the switching losses!

$$\overline{P}_{sw} = f_{sw}\left(\int_{t_1}^{t_1+t_{sw\_on}} i_s v_s dt + \int_{t_2}^{t_2+t_{sw\_off}} i_s v_s dt \right)$$

Losses, Harmonics and EMI

In all power electronic systems, there are stray inductances and capacitances due to interconnections between the power components via wire, conductor plates or any other types of conductors. In a power electronic circuit when we turn on and off a switch, we may charge and discharge stray inductance associated with a current loop as shown in the following figure. The energy stored in the inductor depends on the current magnitude and inductance value. Every time we turn on and off the switch, we lose energy through this inductor which affects the total energy loss and efficiency. It may also create significant over voltage during switching transitions due to high rate of current change.



$$V_{over} = L_s \times \frac{di}{dt}$$

$$E_{L_s} = \frac{L_s \times i^2}{2}$$

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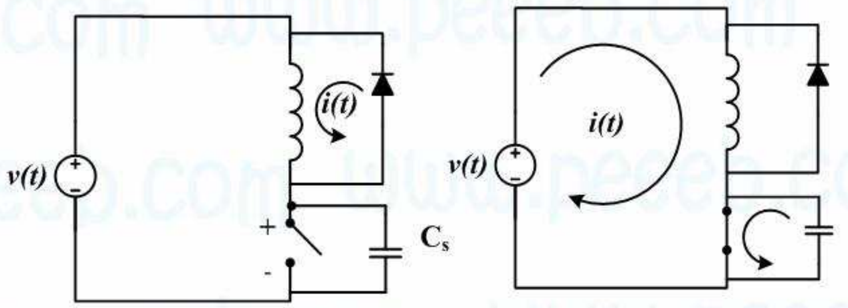
Losses, Harmonics and EMI

Due to capacitive couplings in power converters we may charge and discharge these capacitors when we turn on and off a switch as shown in the following figure. The energy stored in the capacitor depends on the voltage magnitude and capacitance value. Every time we turn on and off the switch we lose energy which affects the efficiency. It may also create significant pulse current when the switch is turned on and the capacitor is discharged through the switch.



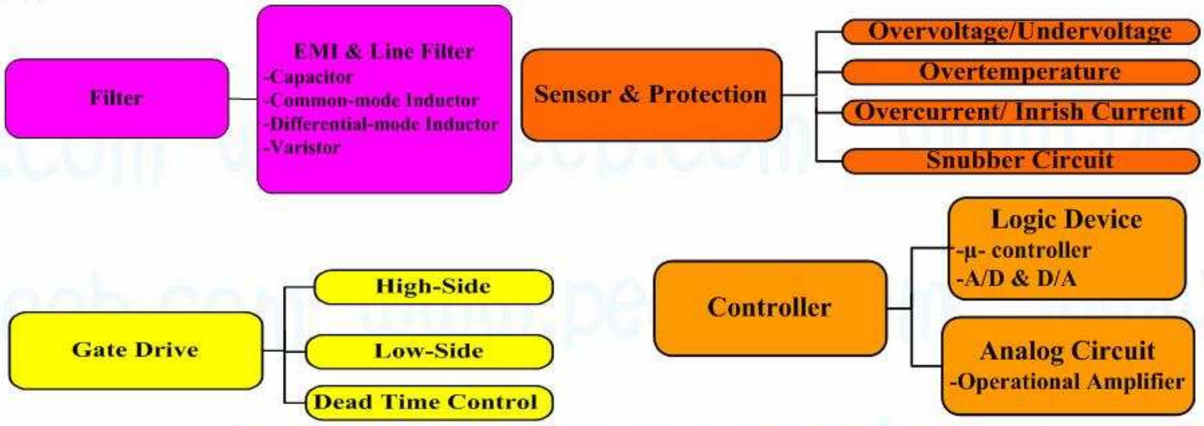
$$E_{C_s} = \frac{C_s \times v^2}{2}$$

Thus, the average power loss due to these stray components over one switching cycle is given by:

$$\overline{P}_{stray} = \frac{(E_{Ls1} + E_{Ls2} + \ldots + E_{Cs2} + E_{Cs2} + \ldots)}{T_{sw}} = f_{sw} \times E_{stray}$$

Losses, Harmonics and EMI

In a Power Electronic System, there are other circuits such as gate drives, controllers, sensors and passive filters which consume power which is named P_{other}.



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Losses, Harmonics and EMI

The total losses in a power electronic system are given by:

$$\overline{P}_{loss} = \overline{P}_{s1} + \overline{P}_{s2} + \ldots + \overline{P}_{stray} + \overline{P}_{other}$$

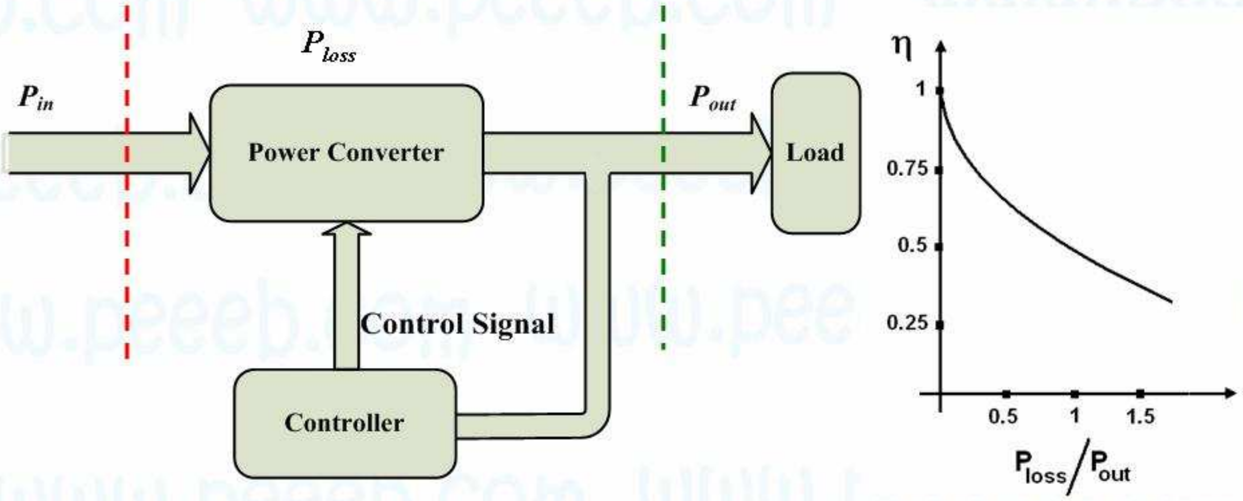
Where P_{si} is a total loss of switch i^{th} which consists of conduction and switching losses.

$$\overline{P}_s = \frac{1}{T_{sw}} \int_0^{T_s} i_s v_s dt = \overline{P}_{cond} + \overline{P}_{sw}$$

Losses, Harmonics and EMI

We can find an efficiency of a system based on input power and total losses.

$$\overline{P}_{out} = \overline{P}_{in} - \overline{P}_{loss} \qquad \eta = \frac{\overline{P}_{out}}{\overline{P}_{in}} = \frac{\overline{P}_{in} - \overline{P}_{loss}}{\overline{P}_{in}} = 1 - \frac{\overline{P}_{loss}}{\overline{P}_{in}}$$



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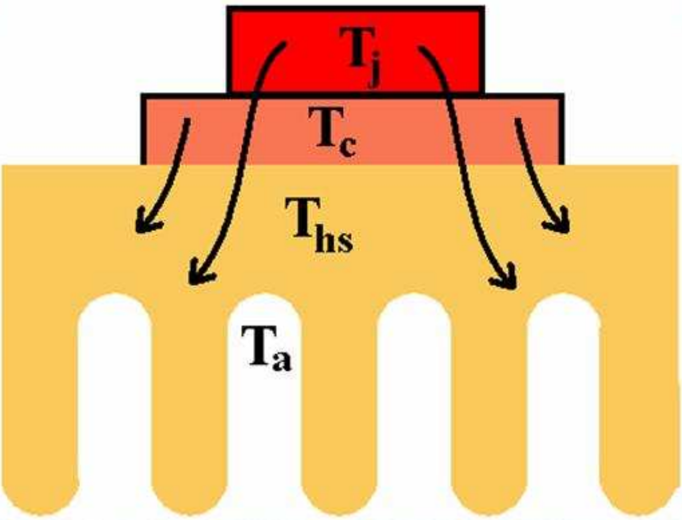
Thermal Problems in a Power Converter

In a power converter, high losses increase the junction temperature of power switches which may damage them if heat is not transferred to ambient. Thus, it may need a heat sink to transfer heat from junction into ambient which increases the cost, size and weight of the power converter.



Losses, Harmonics and EMI

Harmonics:

In power processing, an input voltage/current is chopped based on a pulse pattern which generates a desired output voltage and/or current waveform. This process generates harmonic contents on the output waveform and/or injects high frequency current into the input voltage source.

Switching frequency and passive filters have a significant role in reducing the harmonic magnitude on both sides and we can classify them as:

Load side (DC): Ripple magnitude

Load side (AC): Harmonic contents and THD

Input side (AC): THD and Power Factor

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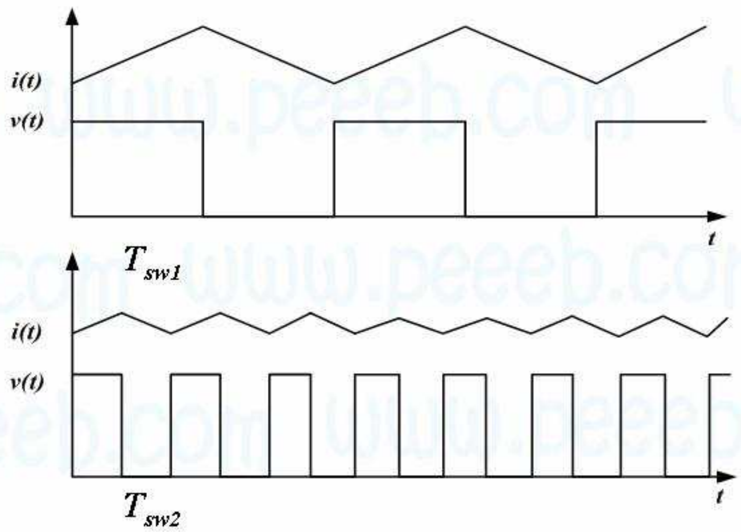
Losses, Harmonics and EMI

The following two output voltage waveforms show that increasing the switching frequency decreases the output ripple but a main drawback is more switching losses.



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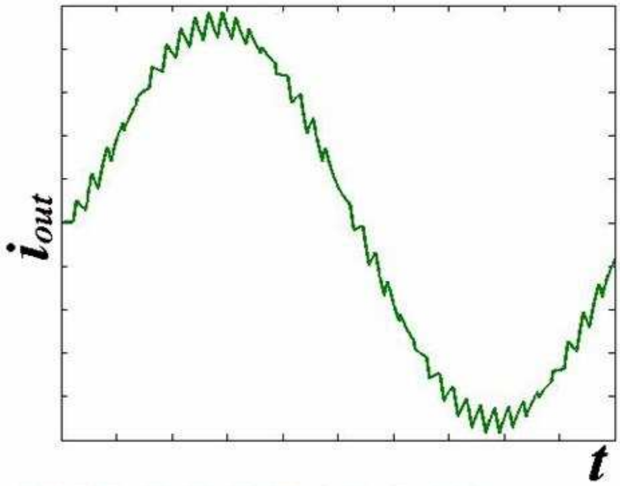
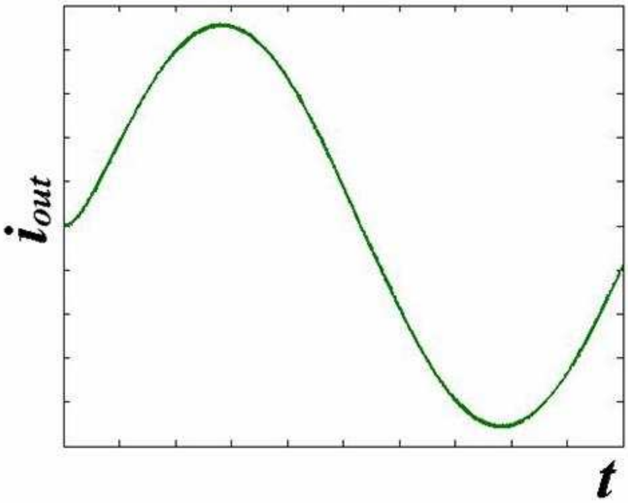
Losses, Harmonics and EMI

The following two output current waveforms show that increasing the switching frequency decreases current harmonics and THD but a main drawback is more switching losses.





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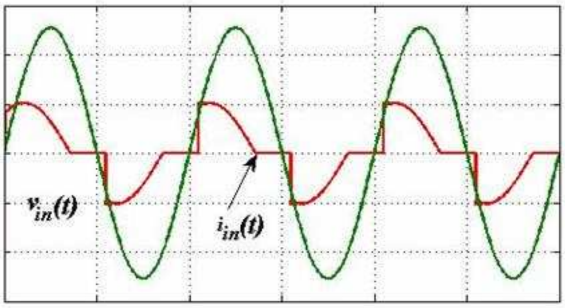
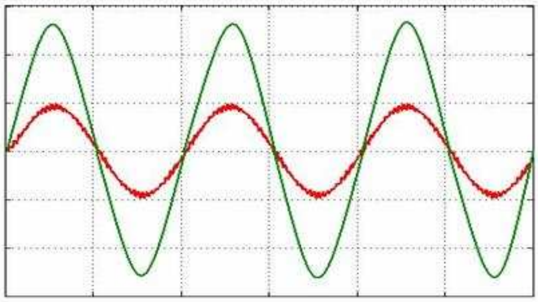
Losses, Harmonics and EMI

The following two input current waveforms show that in an AC-DC converter, the grid may be affected by input current harmonics. A solution is to reduce current harmonics and improve power factors, using a high frequency converter to shape the input current to a sine wave in phase with the input voltage. This converter has more switching losses but the advantage is to improve power quality.





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Losses, Harmonics and EMI

EMI:

Two major sources of EMI in power electronics are *dv/dt* and *di/dt* during switching times. Conducted Emission is a major issue in most power electronic systems.

$$di/dt \rightarrow L_s \rightarrow V_{over}$$

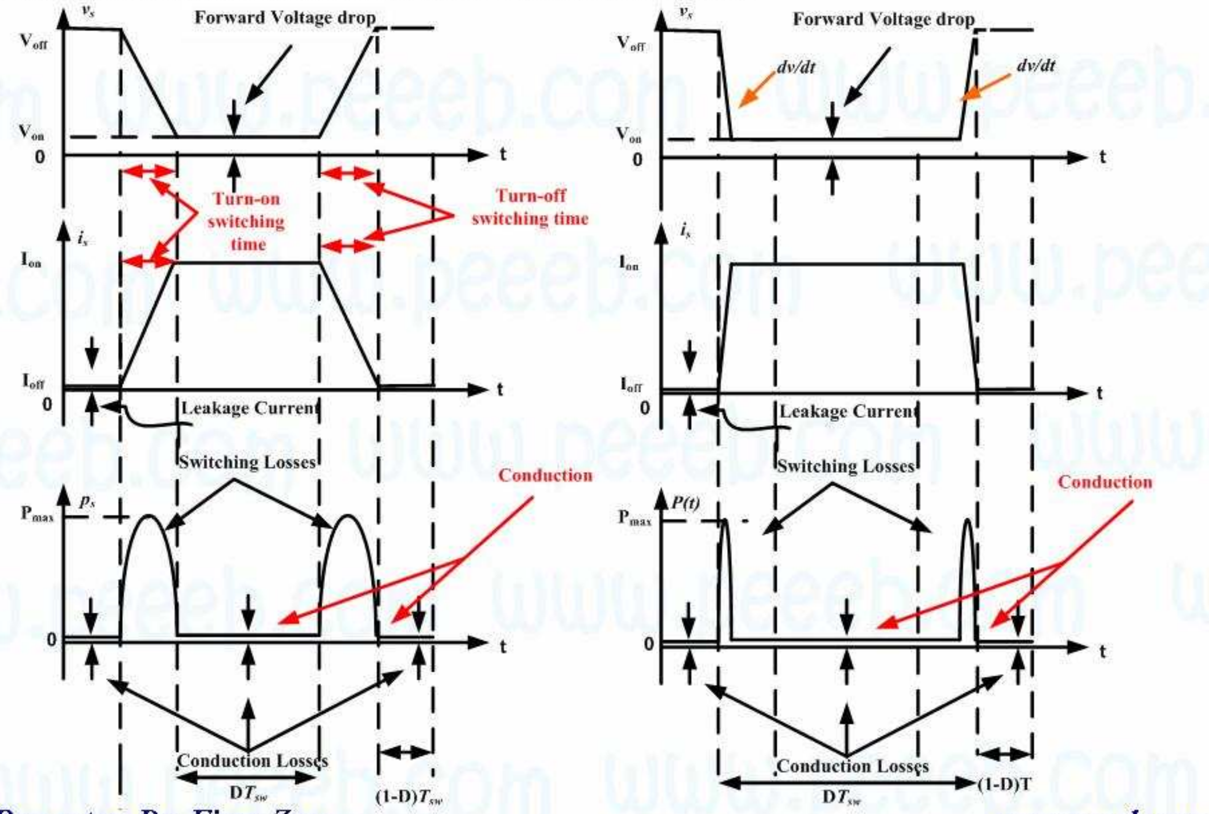
high *di/dt* creates significant over voltage in power converters.

$$dv/dt \rightarrow C_s \rightarrow i_{leakage}$$

high *dv/dt* creates significant leakage current in motor drive systems

Losses, Harmonics and EMI

EMI: effects of different *dv/dt* and *di/dt* on losses



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Losses, Harmonics and EMI

Power switches are the key parts of a power converter and they are classified based on their switching speed and power handling capabilities such as maximum blocking voltage and carrying current.

In Modern Power Converters, achieving high efficiency is a main concern and a key factor which saves energy (less losses) in the converters.

Achieving a high efficient converter is very challenging as we need to compromise with other key factors such as quality and power density.

It is apparent that increasing the switching time and decreasing the switching frequency decreases the total losses but main drawbacks are increasing EMI noise and reducing quality of power converters due to increasing the ripple on output voltage or current.

The main challenges are to have a good understanding of EMI issues in power converters and layout to reduce EMI as low as possible without having extra passive components; and in semiconductor manufacturing to develop a new generation of semiconductor devices to be able to operate at higher temperatures to increase the capabilities of the converter with higher reliability.

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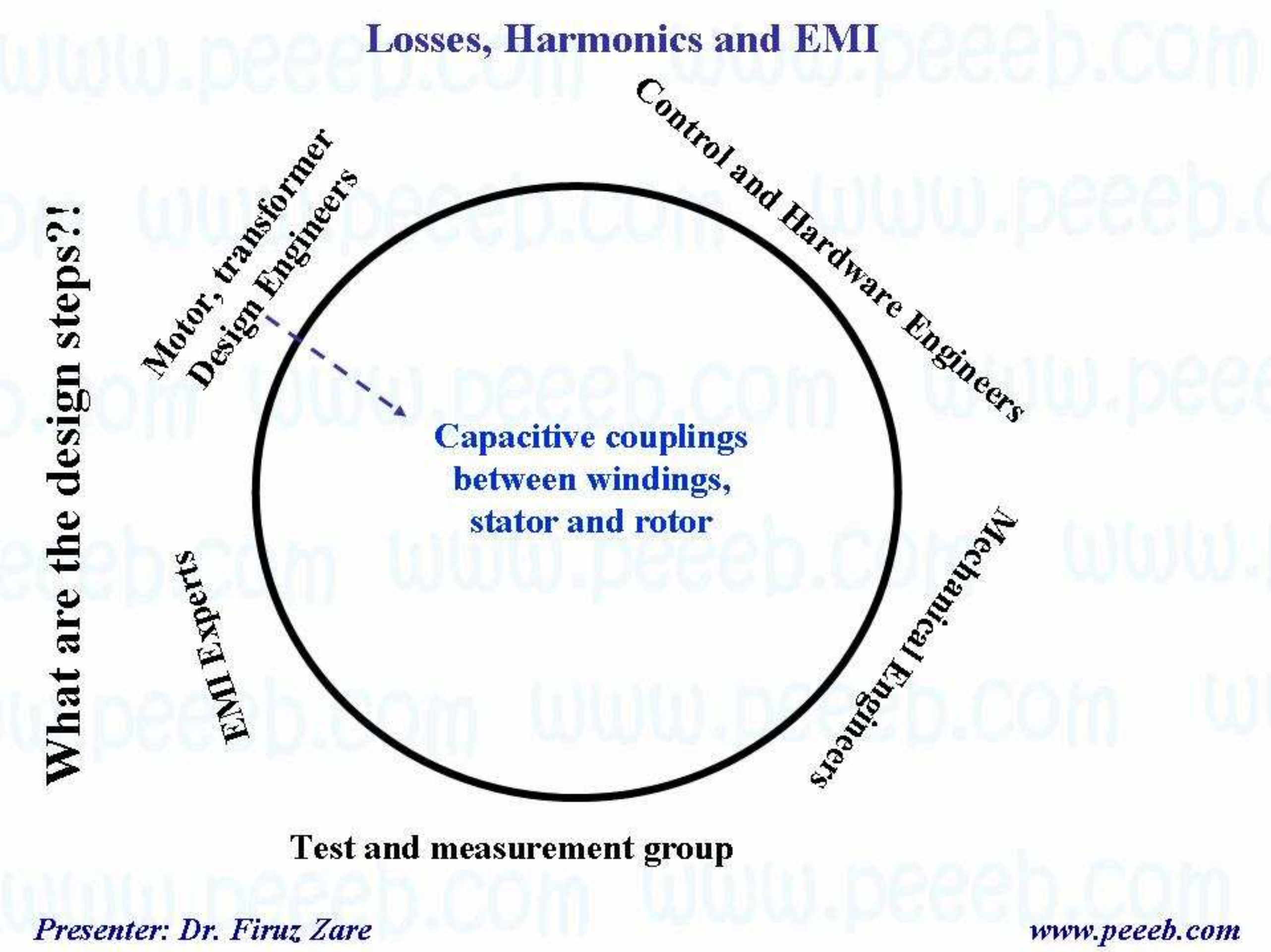
Losses, Harmonics and EMI
What are the design steps?!
Motor, transformer Design Engineers
Control and Hardware Engineers
Capacitive couplings between windings, stator and rotor
EMI Experts
Mechanical Engineers
Test and measurement group
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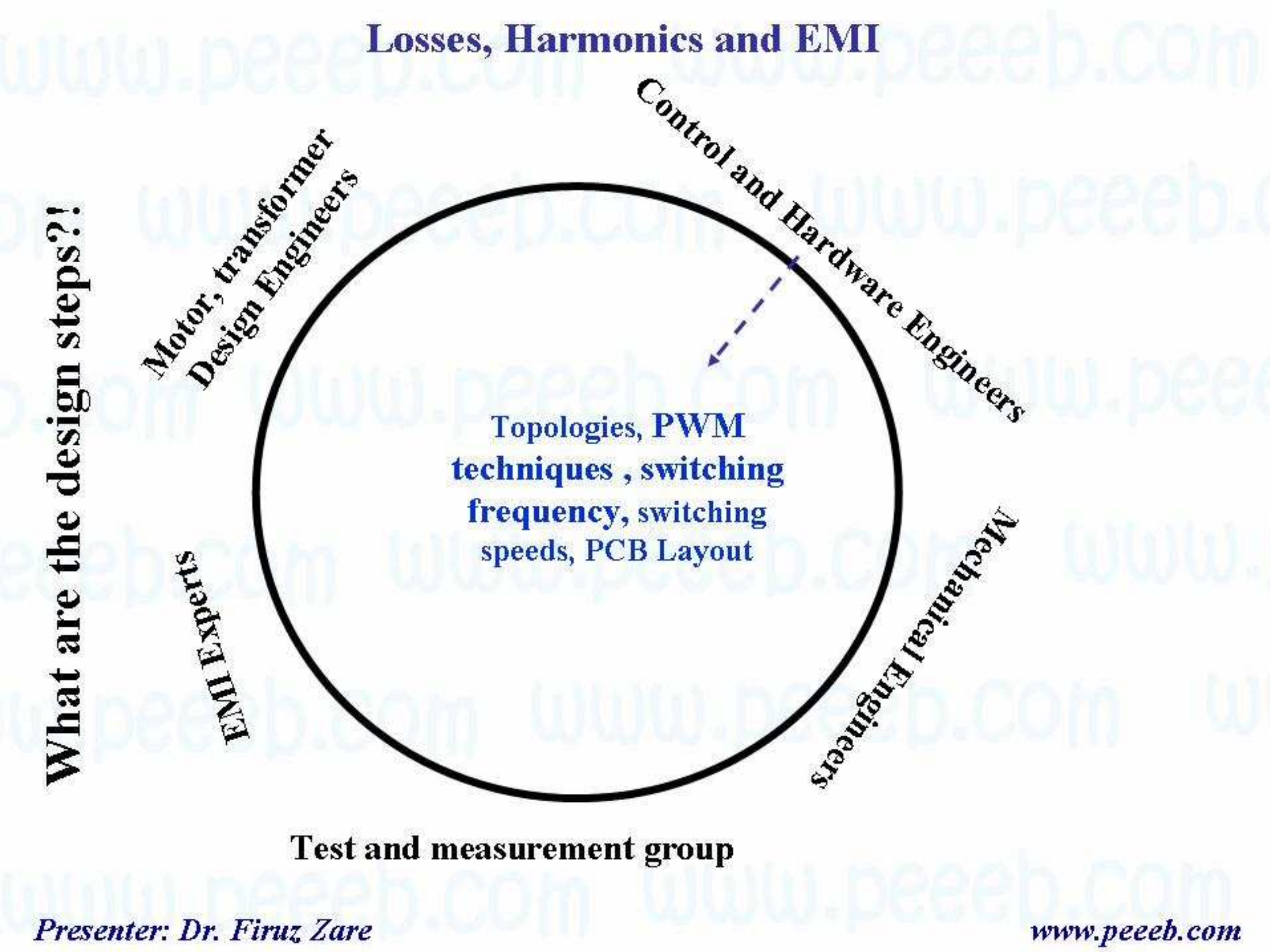

Losses, Harmonics and EMI
What are the design steps?!
Motor, transformer
Design Engineers
Control and Hardware Engineers
Topologies, PWM
techniques , switching
frequency, switching
speeds, PCB Layout
EMI Experts
Mechanical Engineers
Test and measurement group
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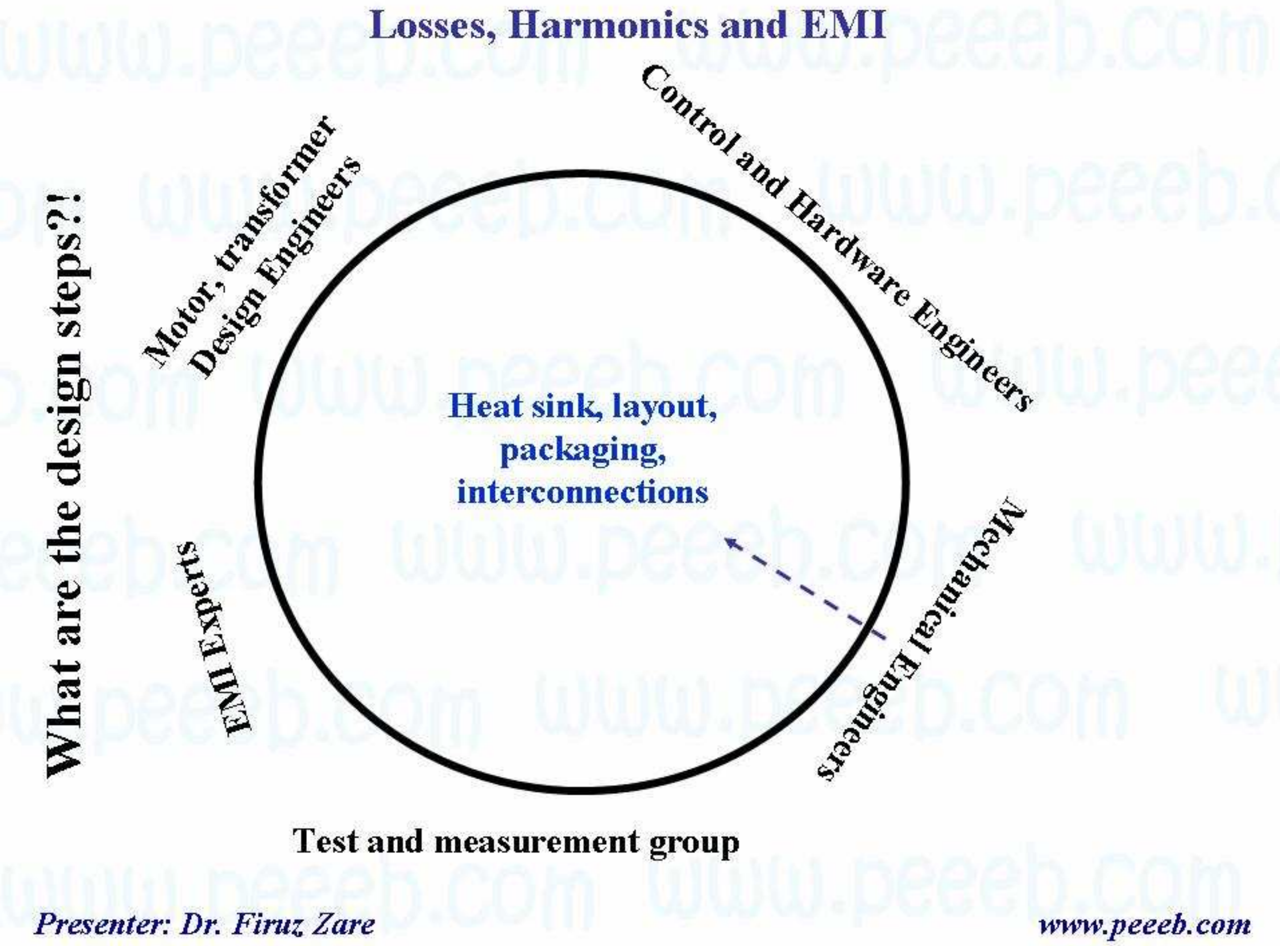
Losses, Harmonics and EMI
What are the design steps?!
Motor, transformer
Design Engineers
Control and Hardware Engineers
Heat sink, layout,
packaging,
interconnections
EMI Experts
Mechanical Engineers
Test and measurement group
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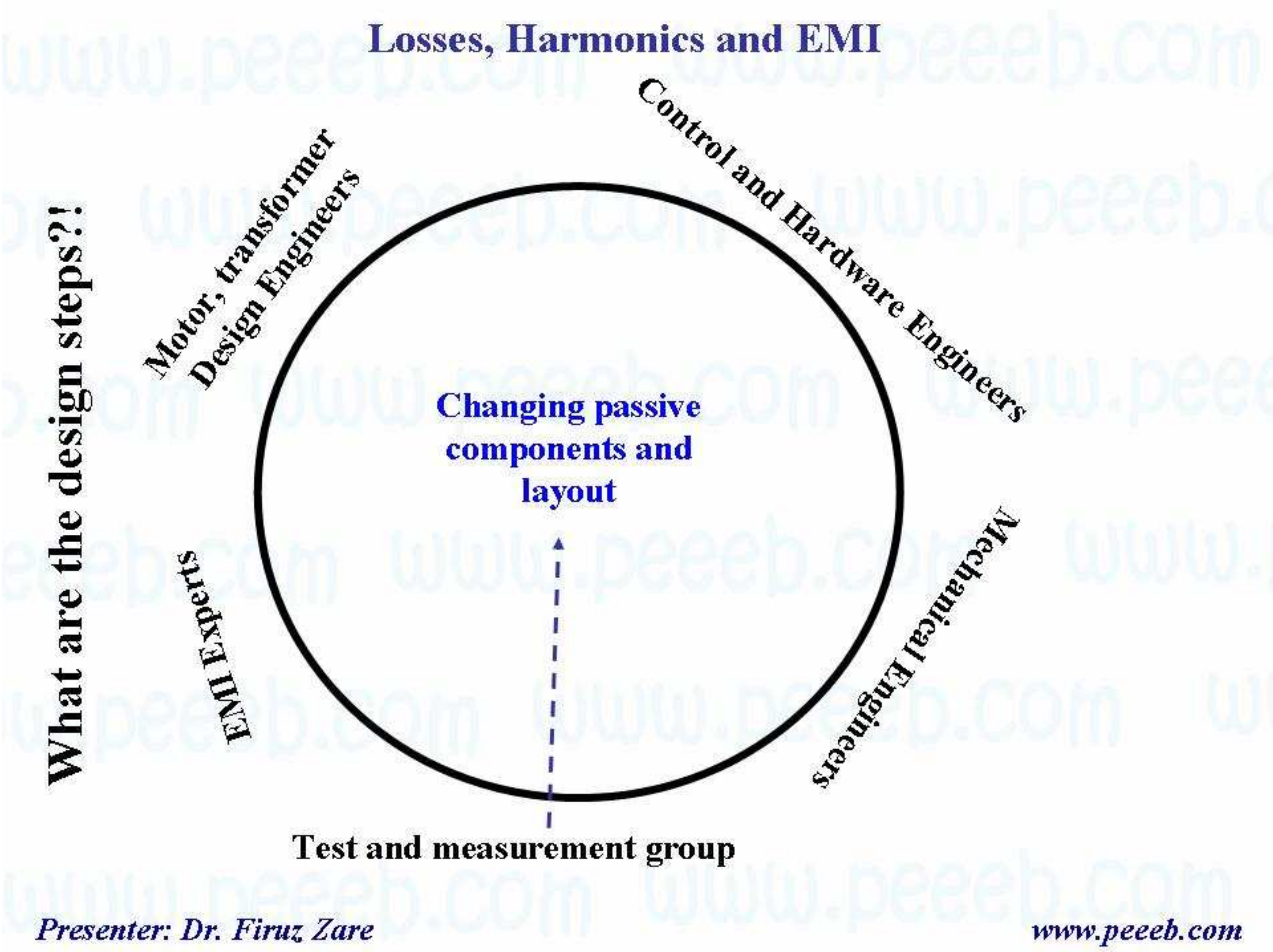

Losses, Harmonics and EMI
What are the design steps?!
Motor, transformer Design Engineers
Control and Hardware Engineers
Changing passive components and layout
EMI Experts
Mechanical Engineers
Test and measurement group
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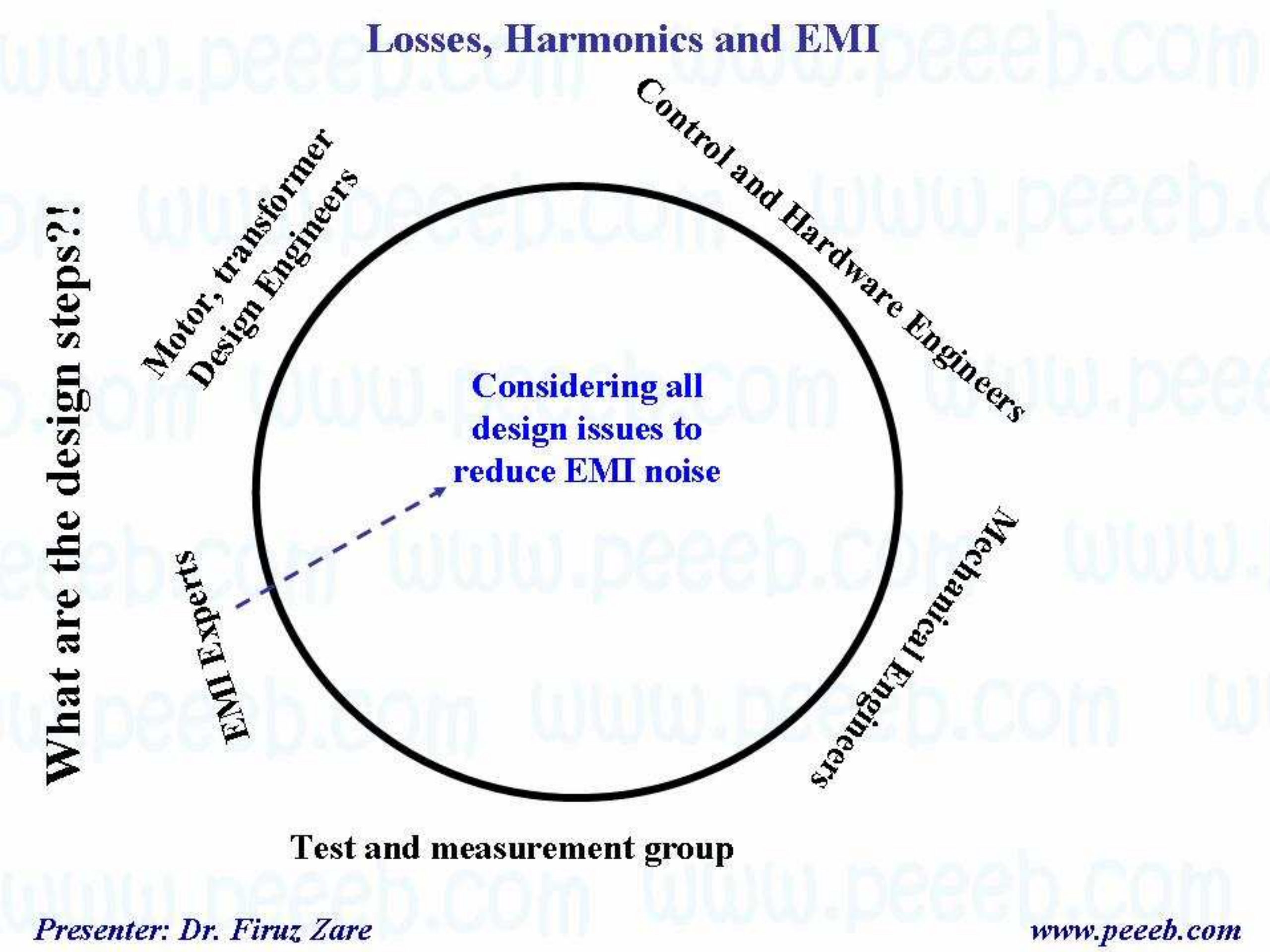
Losses, Harmonics and EMI
What are the design steps?!
Motor, transformer Design Engineers
Control and Hardware Engineers
Considering all design issues to reduce EMI noise
EMI Experts
Mechanical Engineers
Test and measurement group
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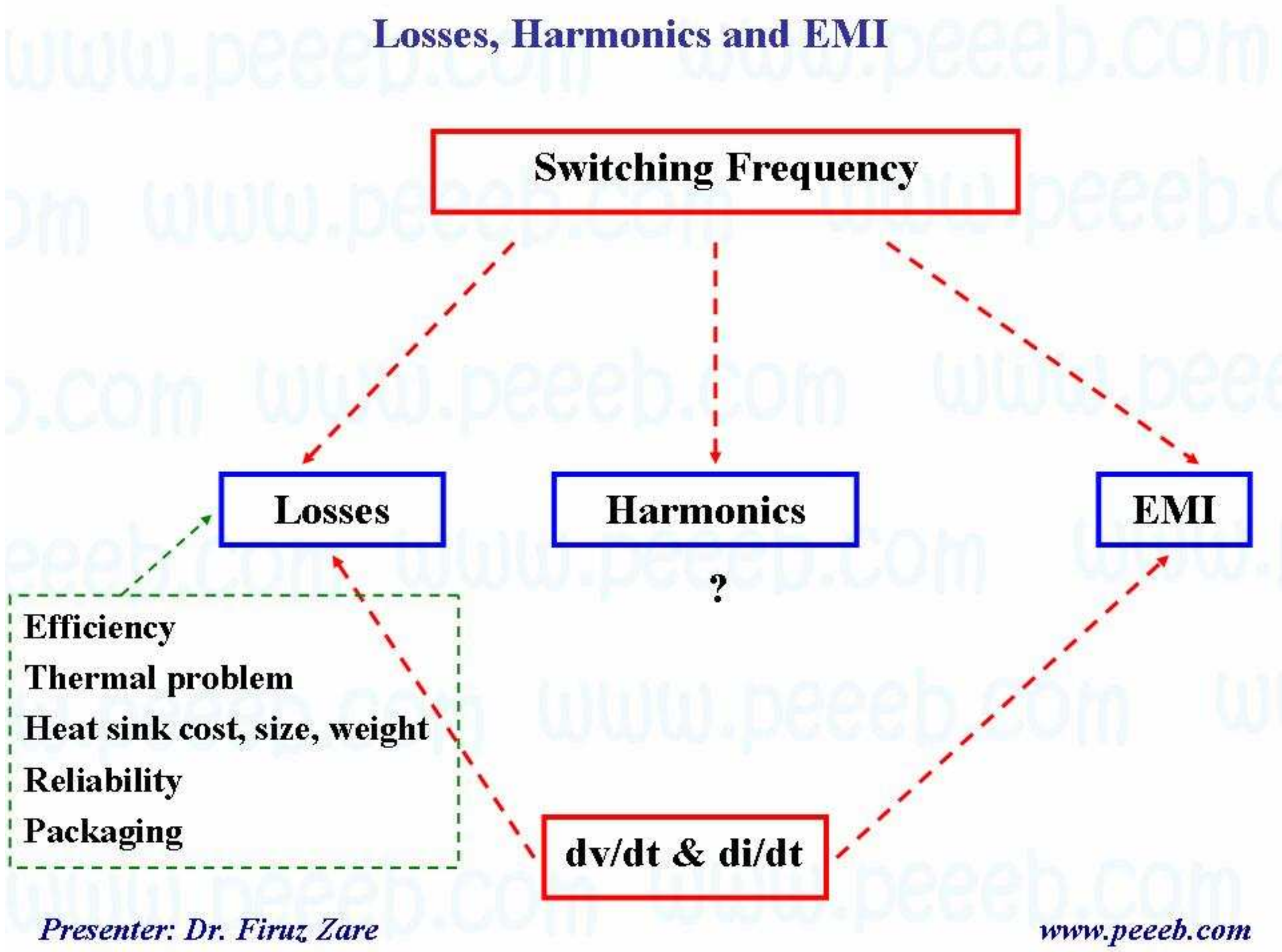
Losses, Harmonics and EMI
Switching Frequency
Losses
Harmonics
EMI
?
Efficiency
Thermal problem
Heat sink cost, size, weight
Reliability
Packaging
dv/dt & di/dt
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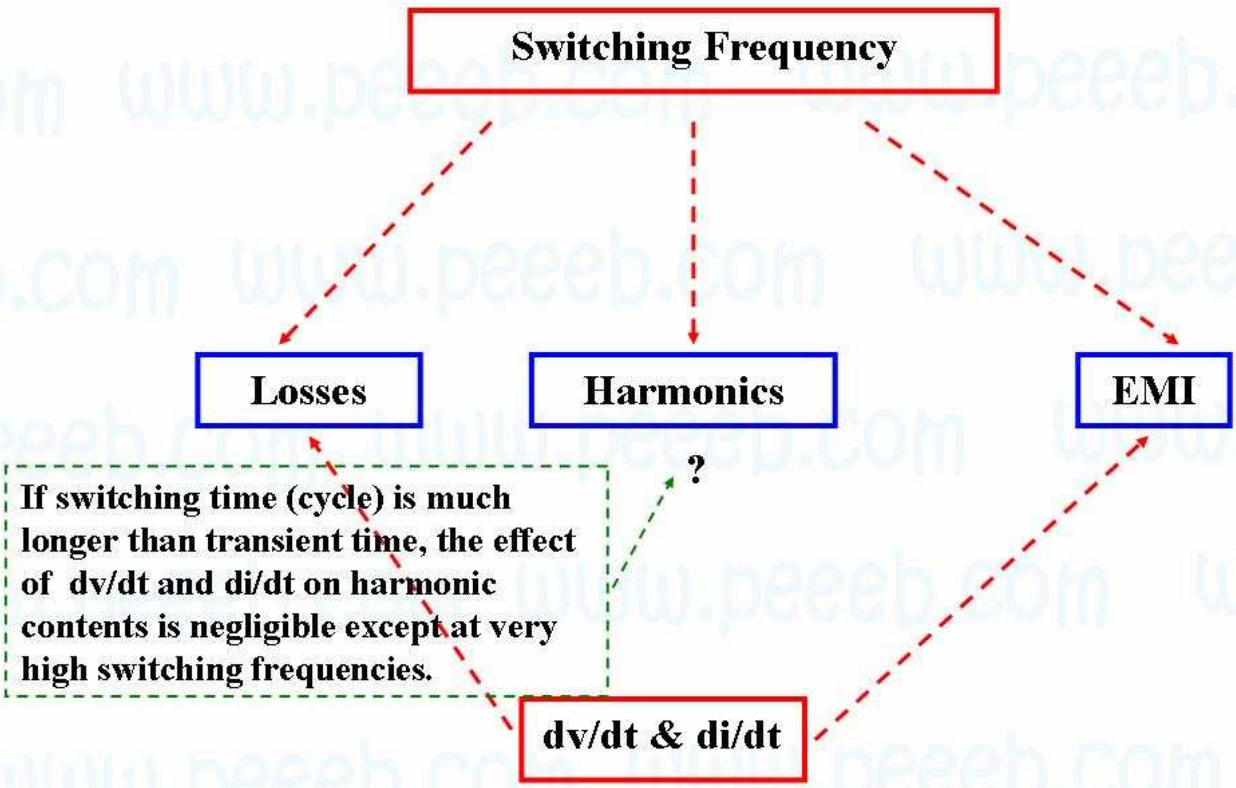
Losses, Harmonics and EMI



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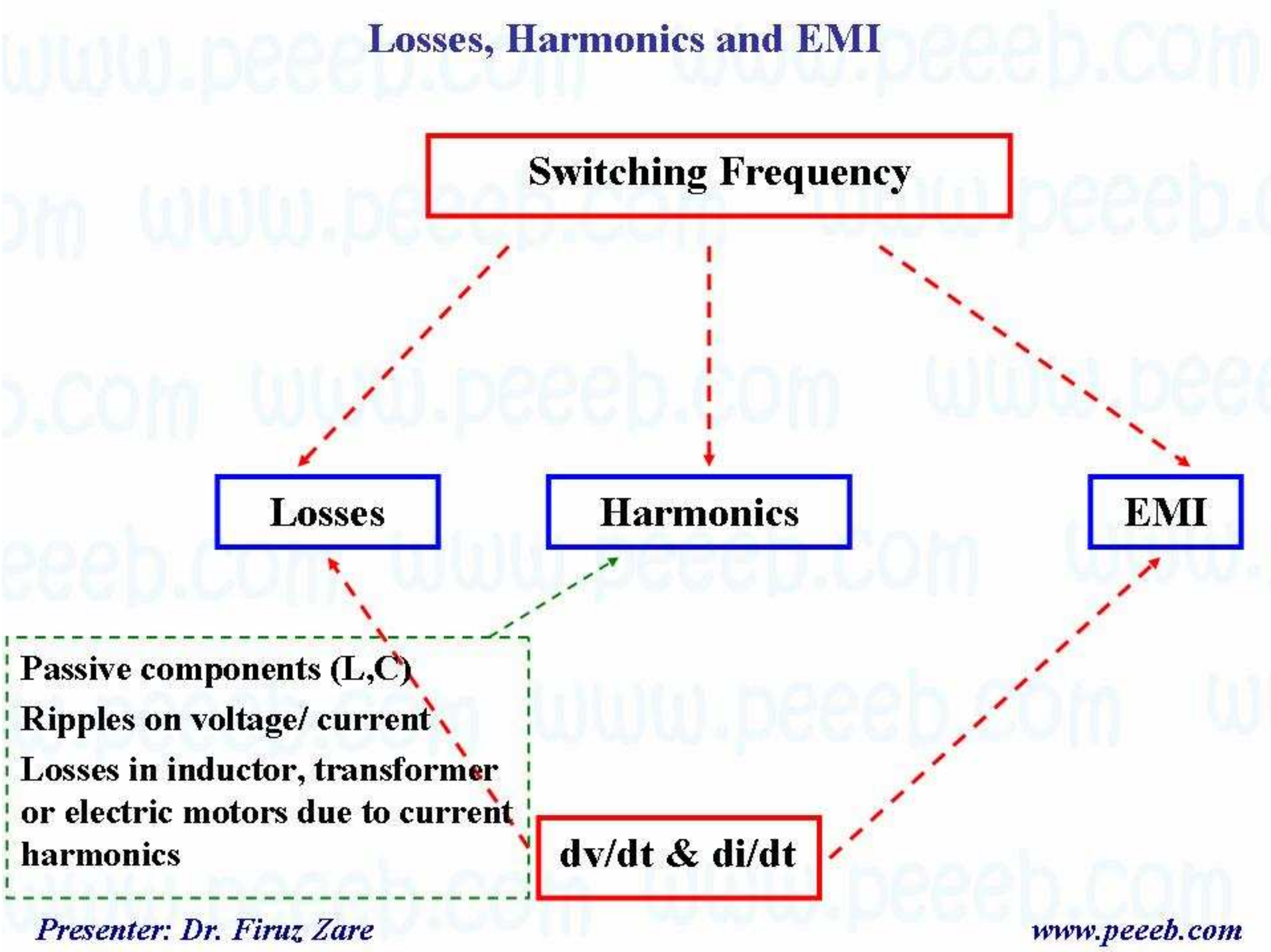
Losses, Harmonics and EMI
Switching Frequency
Losses
Harmonics
EMI
Passive components (L,C)
Ripples on voltage/ current
Losses in inductor, transformer or electric motors due to current harmonics
dv/dt & di/dt
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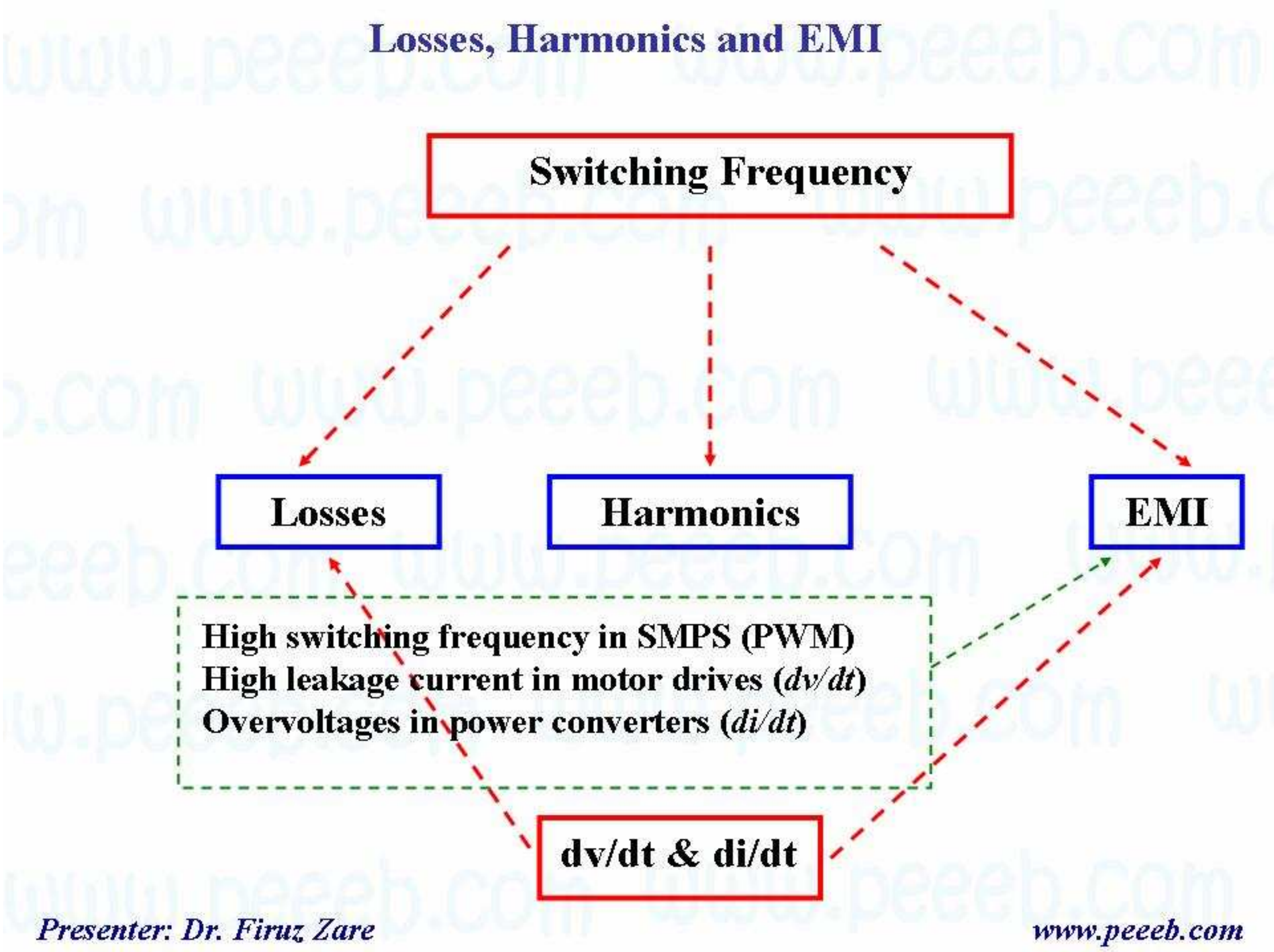
Losses, Harmonics and EMI
Switching Frequency
Losses
Harmonics
EMI
High switching frequency in SMPS (PWM)
High leakage current in motor drives (dv/dt)
Overvoltages in power converters (di/dt)
dv/dt & di/dt
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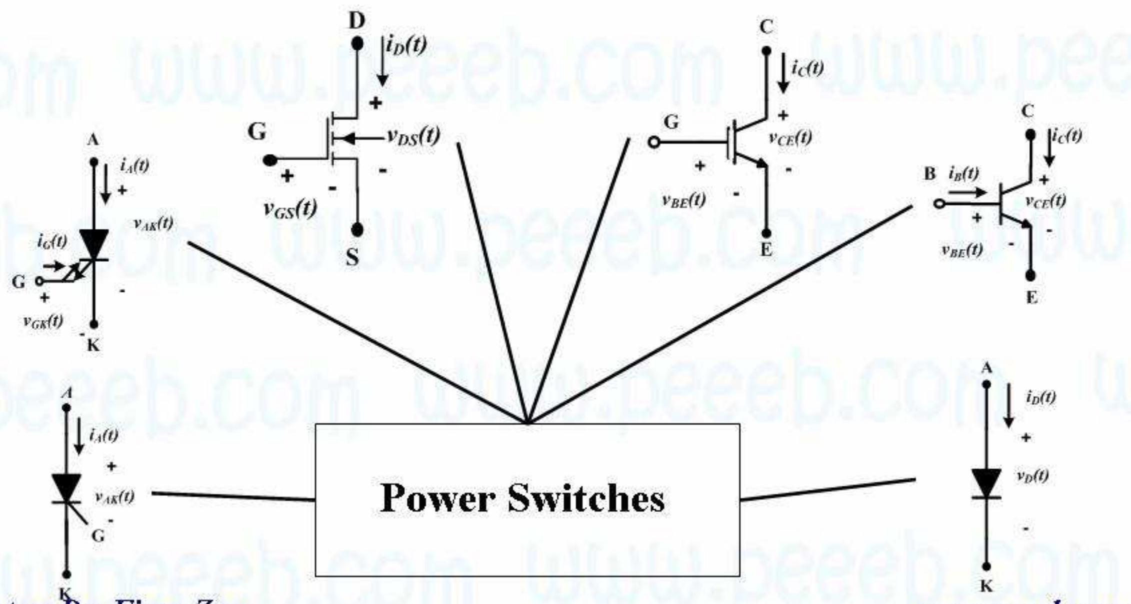
Types of Switches



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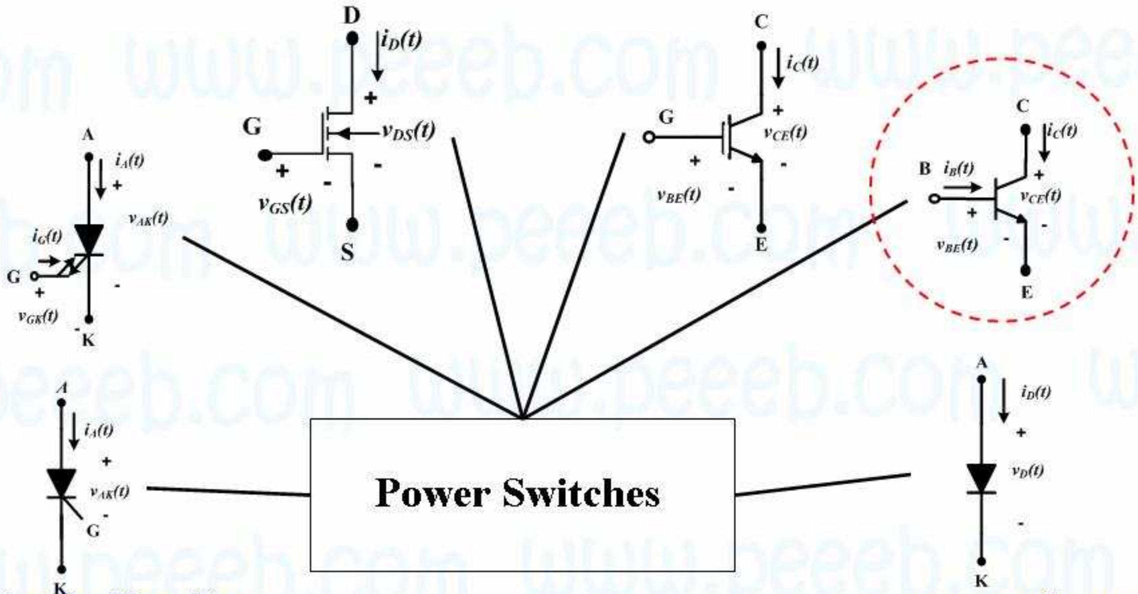
Types of Switches

It is a current control device which needs a sufficiently large base current to turn on the transistor and the base current must be supplied continuously to keep it in the on state. Some types of BJTs have long turn-off times which cause large power dissipation. DC gain is around 5-10 and for high power applications, some should be in cascade configuration.



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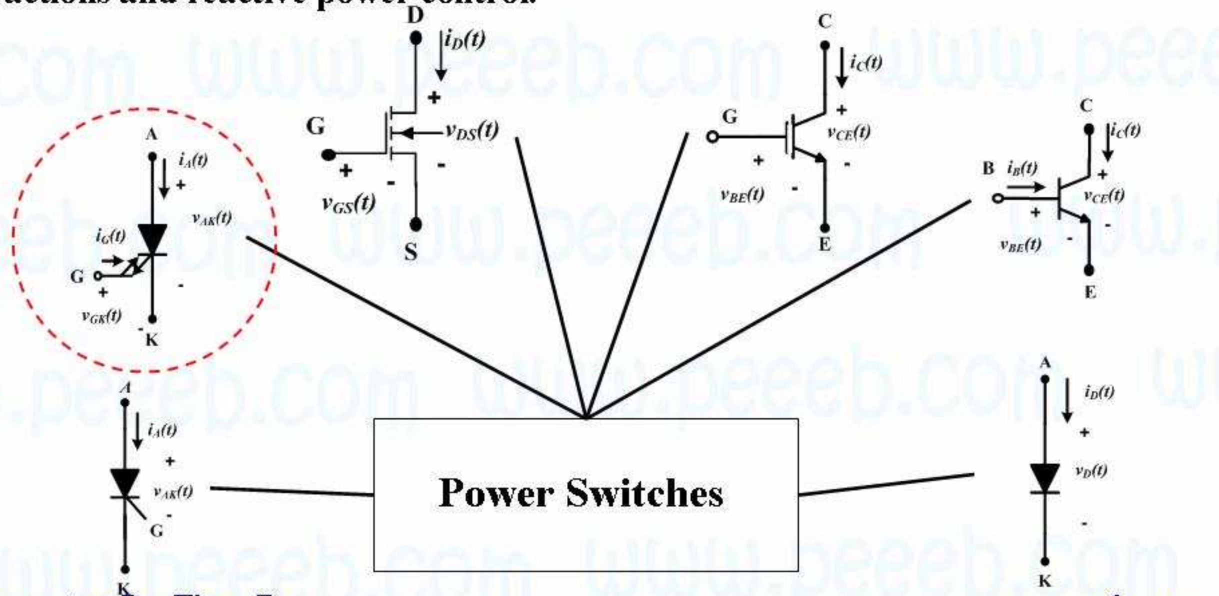
Types of Switches

It is a controllable switch which can block negative voltage. It can handle large voltage up to few kV and large currents up to few kA in a switching range of a few kHz and its maximum switching speed is around 20-30 μs. The GTO can be turned on by a short current pulse and it can be turned off by applying a negative gate-cathode voltage. It is suitable for very high power motor drives, tractions and reactive power control.



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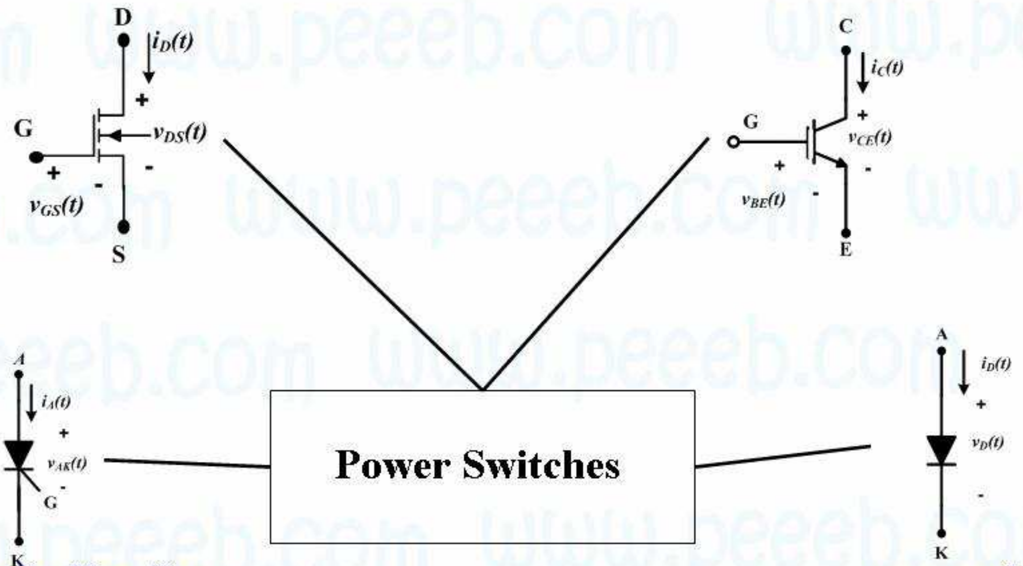
Types of Switches

The most important power switches in modern power converters are:

- **Power Diode**
- **Power Metal-Oxide Field-Effect Transistor (Power MOSFET)**
- **Insulated-Gate Bipolar Transistor (IGBT)**
- ***SCRs have some applications in very high voltage and power systems or low power AC-AC systems***



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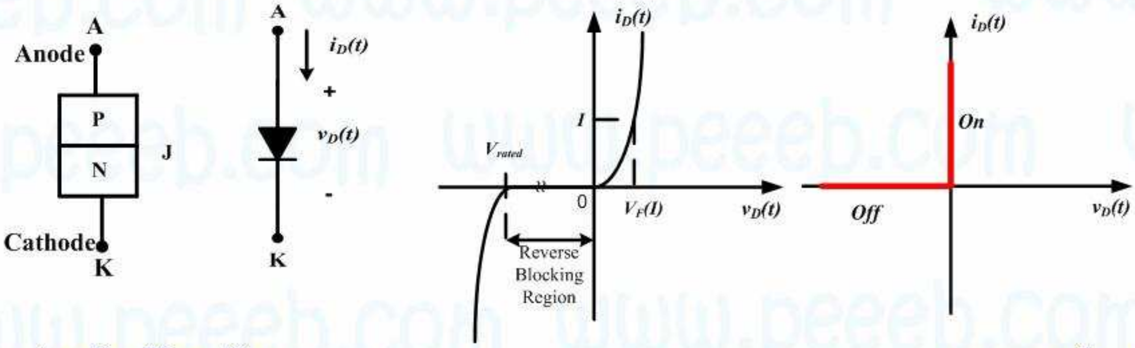
Types of Switches

Power Diodes

A diode is an uncontrolled switch which is turned on and off based on its current and voltage. An ideal diode is turned on when the voltage across the diode is getting positive and the current through the diode depends on circuit and load impedance. A diode can conduct positive current and block negative which has a *i-v* characteristic shown in the following figure. A practical diode cannot block infinite voltage or handle infinite current. Thus diodes are classified based on their capabilities in handling power, voltage and current rates in addition to their speed characteristics.



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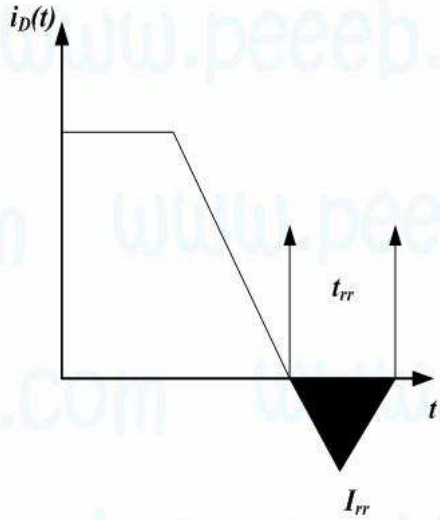
Types of Switches

When a diode is switched off, energy stored between P and N sections must be discharged in order to block the voltage and current. The Electric Charge stored between the P-N junction and the time to discharge it are called Reverse-Recovery Charge, Q_{rr} and Reverse-Recovery Time, t_{rr} which affect switching speed, losses and EMI.
The total charge can be calculated based on the maximum reverse recovery current, I_{rr} and t_{rr}.

Q_{rr} = (reverse recovery charge) = $\frac{1}{2} * I_{rr} * t_{rr}$



Types of Switches

There are different types of diodes such as:

•Schottky diodes which have low forward voltage and are very fast. A main drawback is their capability to block high voltage.

•Fast-recovery diodes which are used in most modern power converters operating at few kV especially in power inverters.

•Line-frequency diodes which can block high voltage up to several kV and handle current rating of several kA but t_{rr} is long compared to other diodes. Thus they are very suitable for high power rectifiers operating at 50-60 Hz.

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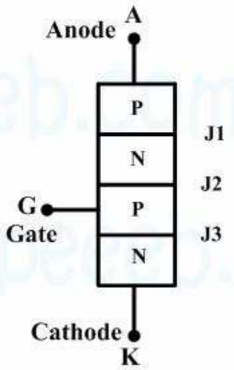
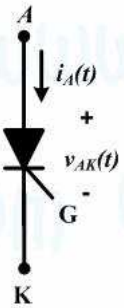
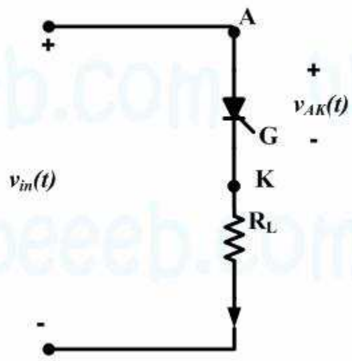
Types of Switches

Thyristor or Silicon Controlled Rectifier (SCR)

A power switch which was very common in the past is Silicon-Controlled Rectifier (SCR) or Thyristor, but they still have an important role in high power high voltage converters due to their advantages in withstanding at high voltage and delivering high current or in low power AC-AC converters in which a simple and cheap converter is required.







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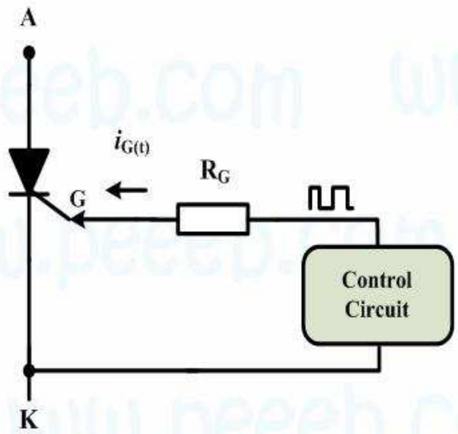
Types of Switches

<u>**How to turn on a Thyristor:**</u> **A positive pulse voltage has to be applied to a gate terminal with respect to the cathode until the anode current reaches a level known as a latching current. The thyristor may turn off just after removing the gate signal if the anode current is less than the latching current.**

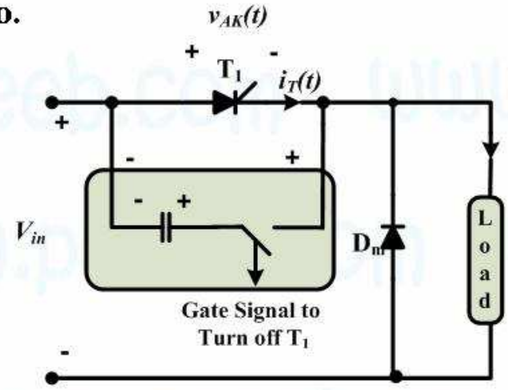
Once a thyristor is in on-state, we can remove the gate signal without changing the switching state of the thyristor. There is a reverse recovery time, t_{rr} and charge Q_{rr} due to some junctions in a thyristor similar to a diode.



Types of Switches

<u>How to turn off a thyristor:</u> We have to notice that a thyristor is not a full-controlled switch. A thyristor can be turned off if the anode current is reduced below a level known as the holding current, and a relatively long time (depends on a negative voltage magnitude across the thyristor) is needed to discharge the PN junctions to recover its blocking state. A forward voltage may turn it on again if the thyristor has not completely reached its blocking state. Turn off time is defined as a minimum time required by a thyristor to withstand forward voltage without switching to an on-state when the anode current is decreased to zero.

To force a thyristor to an off-state, we need an auxiliary circuit with a controlled switch (like another thyristor) to bypass the current through it to reduce the current and apply a negative voltage across the thyristor to discharge the junctions charges.



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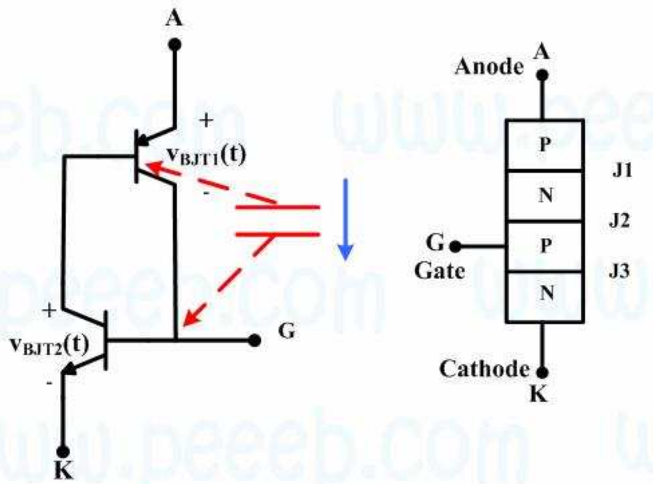
Types of Switches

Fast transient and high voltage stress across a SCR may turn it on at the wrong time and may damage the system.

$I=C_{stray}*(dv/dt)$



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Types of Switches

There are different types of thyristors such as:

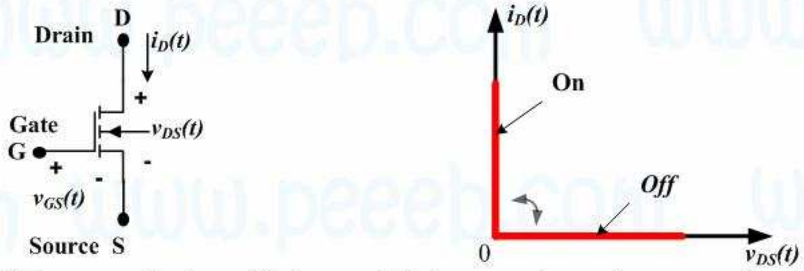
•Phase-control thyristors which can handle few kA and block few kV suitable for power system applications.

•Light-activated thyristors which can be used in high voltage applications such as high voltage DC transmission systems in which galvanic isolation is available through opto coupling gate circuits.

•Low voltage and power thyristors for light intensity control (dimmer) or AC-AC converters suitable for cheap AC motor drives.

Types of Switches

Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)



MOSFETs are fast switches which are tuned on and off by applying a voltage to a gate terminal. They require a continuous gate-source voltage in order to keep them in the on state. The switching time is very short around one hundred nanoseconds which depends on a gate resistor.

MOSFETs are good switches for low voltage applications which require fast switching.

On-state resistance is a main concern at higher voltage ratings.

They are available in different voltage ratings from low voltages (50 V) to 1000V but at high voltage, the current rating is decreased. Normally, the maximum gate voltage is about +/- 20Volts.

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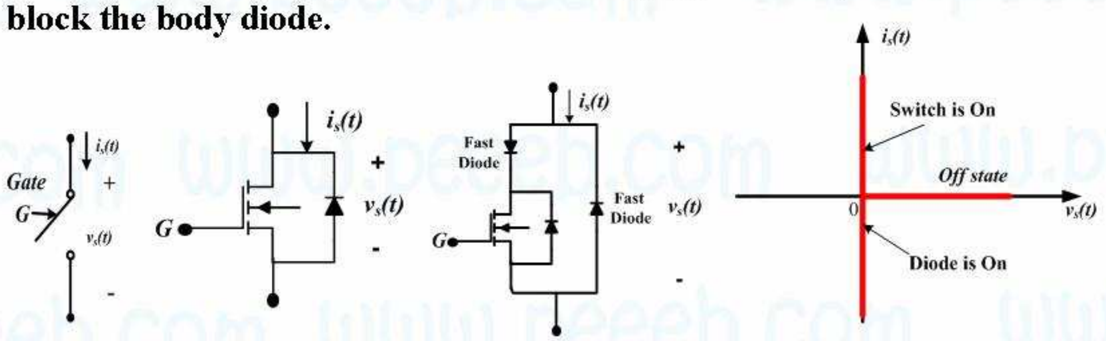
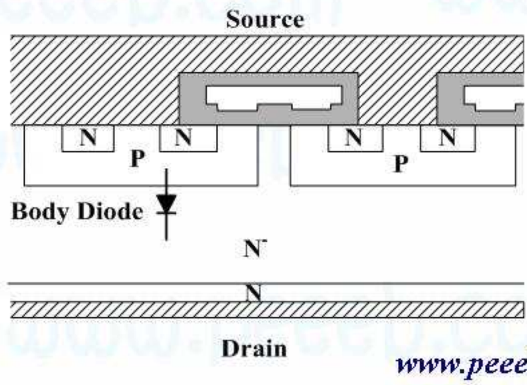
Types of Switches

Look at the data sheet and find the body diode characteristics and reverse recover energy. For fast switching applications, use fast diodes to block the body diode.



The body diode cannot handle high peak current and is also slow which has a significant switching loss.



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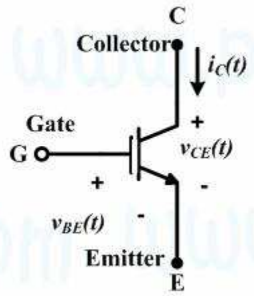
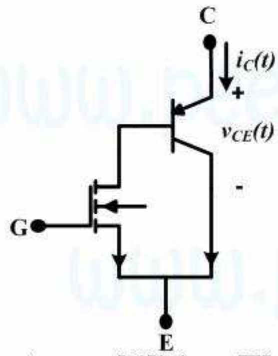
Types of Switches

Insulated Gate Bipolar Transistor (IGBT)





IGBTs are fast switches with high voltage and current capabilities. They are commonly used in most of high power converters when fast switching is required. The turn on and off process is similar to MOSFETs with high gate impedance which requires a small amount of energy to switch the device.
Turn on speed of the IGBT can be controlled by a gate resistor.
IGBTs have turn-on and turn-off times in the order of microseconds and are available in ratings of 2-3kV and 1200A with on-state voltage of 2-3 V.
If an IGBT structure contains a parasitic thyristor, it should not be turned on or else the gate will lose the ability to turn off the device.

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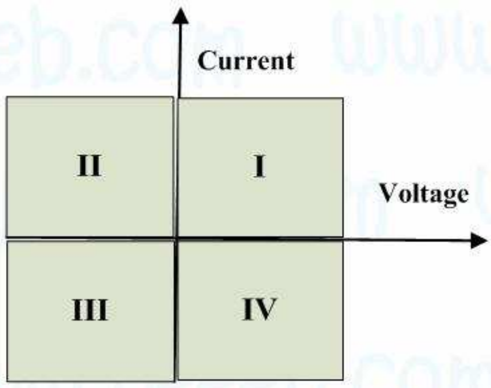
Types of Switches

When we design a power converter, it is crucial to understand directions of power flow which define what type of switches we need to handle that power flow.

As most of loads are resistive-inductive, thus a switch should handle bidirectional current and sometimes they should block positive and/or negative voltages.

For these applications, we need to combine some switches in parallel or series in order to have a flexible switch to operate in different quadrants as shown in this figure.



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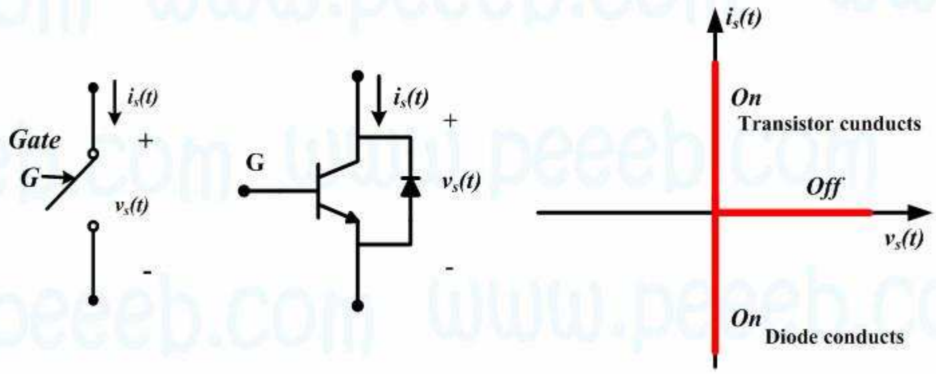
Types of Switches

Bidirectional Switch

A controlled switch like an IGBT with an anti-parallel fast diode as shown in this figure gives a new combination named as a two-quadrant switch which can handle bidirectional current.

This type of switch is very common in DC-AC converters.

It can block positive off-state voltage.

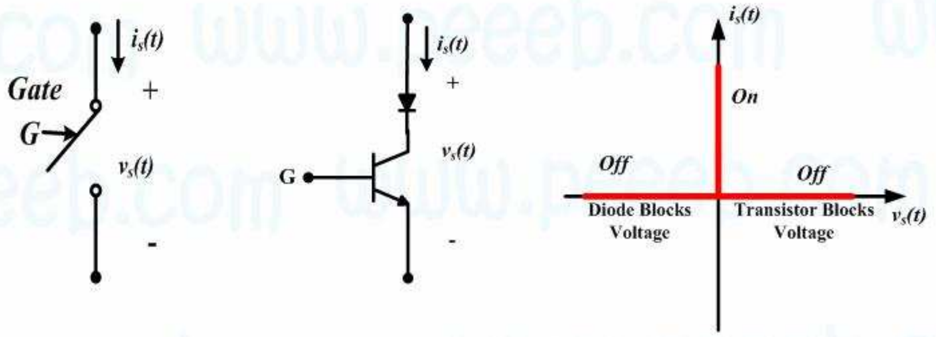


Types of Switches

Bipolar Switch

A controlled switch like an IGBT in series with a fast diode as shown in this figure, gives a new combination named as a two-quadrant switch which can handle bipolar voltage.

This type of switch is not very common but it is suitable for current source inverters. It can block positive and negative off-state voltages.



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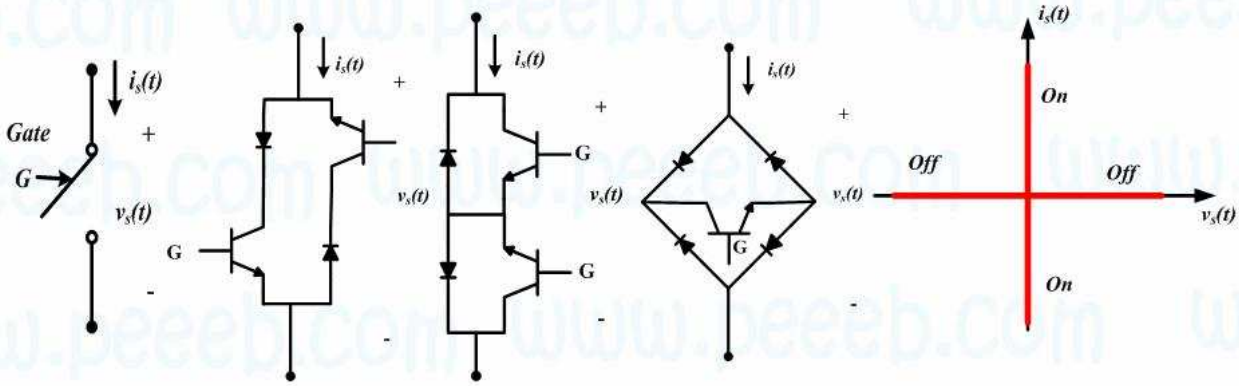
Types of Switches

Bidirectional and Bipolar Switch

In some applications power switches should have bidirectional and bipolar capabilities. Three different combinations shown here can achieve this characteristic.



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Gate Drive

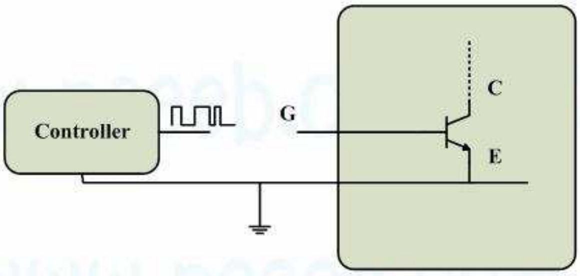
In a power electronic converter, with at least one controlled switch, there is a need to have a gate drive in order to turn on and/or off a power switch at a desired switching speed.

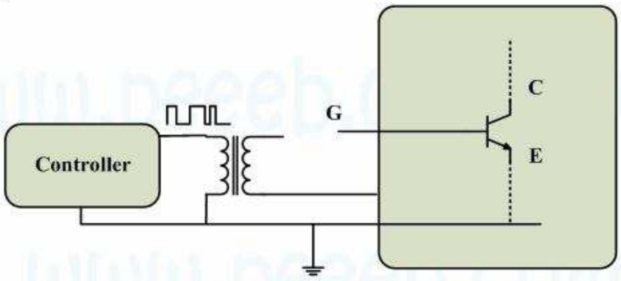
In this section, we just concentrate on three main power switches, Thyristors, IGBTs and MOSFETs.

Thyristor is a switch which is turned on based on a gate current while a MOSFET or IGBT needs enough voltage to be turned on or off.

Another issue in turning on and off a power switch is a galvanic isolation which enables us to provide enough gate voltage with respect to cathode or emitter or source.

Power switches should be protected by a gate drive circuit when over-voltages or over-currents or over-temperatures are sensed.





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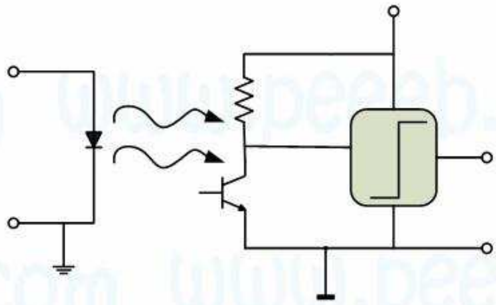
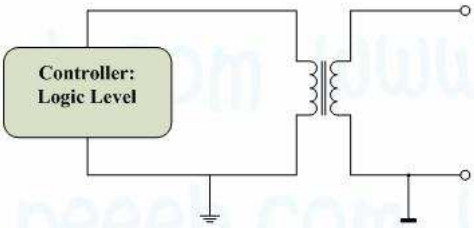
Gate Drive





Opto-couplers are suited devices for providing galvanic isolation and to drive power IGBTs and MOSFETs used in different power converters.
A main drawback is that the opto-couplers require a separate power supply.
A gate drive based on a pulse transformer is a simple and highly noise-immune topology providing isolation. A transformer can only transfer AC signals to the secondary and they can be used for duty cycles between 35% and 65%.
A main drawback of this topology is the leakage inductance of the transformer which may affect the gate drive performance.

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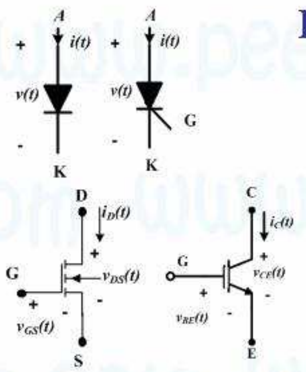
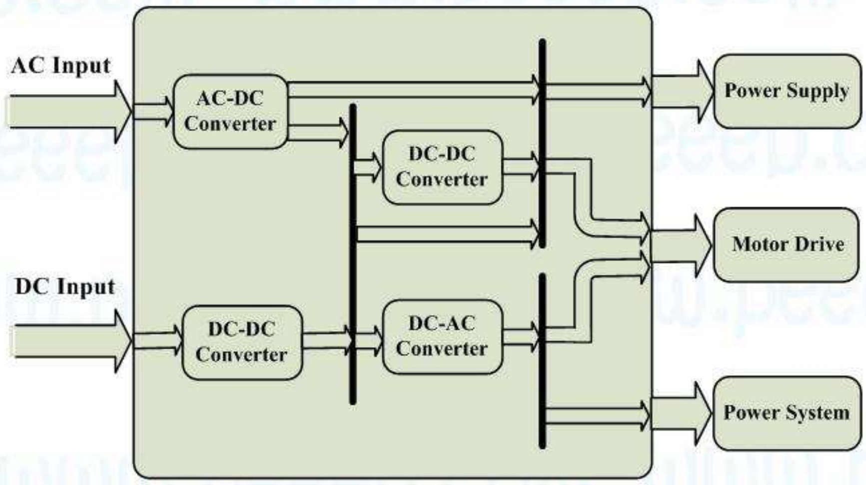
Power Switches in Different Applications





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