Practical Considerations in the Design of Power Converters

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“Power Electronics” can be considered as:

“The technology associated with the conversion, control and conditioning of electric power from its available form to the desired electrical form, by the application of electronics”
Why Power Electronics?

- Power Electronics is one of the fastest changing technology today, having gone through dynamic changes in the last several decades.
- The solid state era, which has accelerated automation in industry, has led to increased R&D in Power Electronics, in order to meet the demands of increased productivity and improved product quality.
- The technologies involved have been going through constant change, depending on the demands of its diverse and ever-expanding application area.
- Today, significant developments in non-power-electronics areas are catalyzing spontaneous development in power electronic converters for those specific areas.
- The future of Power Electronics is truly multi-disciplined and multi-solutioned in nature.
Importance of Power Electronics

• Conversion of electrical energy from one form to another of choice.
• Smooth control of electrical power flow.
• High efficiency involved in the above processes.
• High reliability of the controlling system.
• Compact size of the controlling system.
Major Power Electronics
Application Industry in India

• General Industries
  ✓ Manufacturing
  ✓ Process
• Battery Installations
• Telecommunications
• Railways
  ✓ Stationery
  ✓ On-board
• Defence
  ✓ On ground
  ✓ In-flight
• Commercial Offices
• Consumers
• Lighting Control
• Power Sector

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Requirements of Technology Developments

- Clear understanding of the system
- Definite technical backup
- Well designed for high reliability
- Definite time frame for development
- Uninterrupted technical support
- Appropriate manpower for the development
- Smooth flow of funds
Technology Demand

INDEGENOUS

vs

IMPORTED

Which is better?
Advantages of Indigenous Technology

- Custom designed to the requirements
- Ensures that almost all components can be easily sourced
- Lower cost
- Can be easily modified in future
Advantages of Imported Technology

- Readily available for production
- Modern technology involved to give best performance
- High Reliability
- A free trip abroad
Meeting Indigenous Technology Demand

- In-house R & D

- R & D Centers

- Design Consultants

- EXTERNAL

Technology Demand

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Design Inputs

- Environmental Specifications
- Hardware Specifications
- EMI/EMC Specifications
- Mechanical Specifications
- Other Specifications
- Electrical Specifications
- Cost Factor

SELECTED TOPOLOGY

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ELECTRICAL SPECIFICATIONS

- Input Voltage Range
- Input Frequency Range (if ac input)
- Input Current Waveform/Ripple
- Input Power Factor (if ac input)
- Output Voltage. If adjustable, then range.
- Output Voltage regulation.
- Output Voltage Waveform/Ripple
- Output Current Limit. If adjustable, then range
- Output Frequency Range (if ac)
- Output Transient Response
- Efficiency
- Electrical Isolation from Input to Output
- Reverse Polarity Protection (if dc)
MECHANICAL SPECIFICATIONS

- Overall Size
- Overall Weight
- Specific Shape
- Mounting Plan
- Type of Enclosure
- Ventilation, if any
- Openings to access inside
- Electrical Termination Locations
- Metering panel, if any
- Operating Switches, if any
- Color of Enclosure
HARDWARE SPECIFICATIONS

- Type of Connections/Connectors
- Type of Metering, if any
- Type of Push-Buttons /Switchgear
- Type of Indicators (audio/visual)
ENVIRONMENTAL SPECIFICATIONS

- Type of Cooling
- Ambient Temperature Range
- Maximum Altitude of operation
- Maximum Temperature rise in components
- Humidity/Dust/Salty atmosphere
EMI / EMC SPECIFICATIONS

- Conducted EMI
- Radiated EMI
- Susceptibility to Conducted EMI
- Susceptibility to Radiated EMI
OTHER SPECIFICATIONS

- Skin Effect Losses
- Input Surges/abnormalities
- Digital Settings & Display
- Computer Interface
- Parallel operation
- Synchronization with others
- MTBF specifications
Selection of Switching Frequency

Available Power Semiconductor

Available Magnetic Material

Specifications to be met

Available Isolation & Control

Other Factors

CHOICE OF SWITCHING FREQUENCY

SELECTED TOPOLOGY

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MAGNETIC MATERIALS

- Cold Rolled Non-Oriented Steel (CRNO)
- Cold Rolled Grain Oriented Steel (CRGO)
- Laser Scribed CRGO
- Powdered iron Core
- Amorphous Core (METGLAS)
- Ferrite Core
POWER SEMICONDUCTORS

- Bipolar Power Transistors (upto about 30kHz, 250W power)
- Power MOSFETs (upto about 200kHz, 1kW power)
- IGBTs (upto about 30kHz, 1kW or higher power)
- SCRs in all range of power, mostly in 50Hz applications
- Triacs in specific 50Hz applications
- Ultra Fast Recovery Diodes
- Schottky Diodes
CONTROL & ISOLATION

- Analog Control
- Analog – Digital Hybrid Control
- Microcomputer based Digital Control
- DSP and FPGA Control
- Non-isolated Drive Scheme
- Pulse Transformer Isolation
- Optical Isolation
- Floating Drivers
DESIGN STEPS

Clear understanding of operation of each stage

Control Circuit  Mechanical Design

- Worst case condition for current and voltage in each stage
- Estimate Efficiency of each stage, hence input power of each stage
- Estimate average current, peak current and peak voltages for semiconductors. Apply Safety Margins
- Estimate rms current, voltages and worst frequency of magnetics. Peak current and peak voltages may also be needed

Semiconductors & Snubbers  Magnetics  Cooling  Fuse, Switches, Connectors  Others

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Transformers in Power Electronics

- Transformers are used in Power Electronics to change the magnitude of voltage and/or to provide galvanic isolation.
- Thus, transformers can carry significant amount of high frequency currents.
- Transformers can operate with either ac voltages or pulsating dc voltages.
- No transformer is ideal, so their behaviour depends upon the applied waveform & frequency.
- The peak flux density depends on the peak instantaneous current through its magnetising inductance.
Flux Reset in Unidirectional Excitation Transformers

\[ e = N \frac{d\Phi}{dt} \]

- If \( E = N \frac{d\Phi}{dt} \)
  - \( \frac{d\Phi}{dt} = \text{constant} \)

- If \( E = 0 \)
  - \( \frac{d\Phi}{dt} = 0 \)
Magnetic Materials

• CRNO Core
• CRGO Core
• Laser Scribed CRGO
• Powdered Iron Core
• Amorphous Core (METGLAS)
• Nanocrystalline Core
• Ferrite Core
Si-Steel Based Cores

• Cold Rolled Non Oriented cores are made of silicon steel, of about 0.35mm thickness and flux density about 1.5 Wb/sqm

• Cold Rolled Grain Oriented cores are made of silicon steel, of about 0.3mm thickness and flux density about 1.5 Wb/sqm

• Laser Scribed CRGO cores are made of silicon steel, of about 0.3mm thickness and flux density about 1.5 Wb/sqm. A diagonal scribing across the surface at equal intervals reduces the total core loss.

• Powdered Iron Cores are made of finely powdered silicon steel, bonded together by epoxy adhesive. Thus, a distributed air gap inherently exists in the solid core structure.
Amorphous Cores

- Amorphous metals are produced by using a rapid solidification technology where molten metal is cast into thin solid ribbons by cooling at a rate of one million deg C/second. Amorphous magnetic metal has high permeability due to no crystalline magnetic anisotropy. The ribbons are about 0.03mm thick, held together by adhesives capable of withstanding high temperatures. The maximum permissible flux density is about 1.2 Wb/sqm.

- Nanocrystalline amorphous metal is produced by rapidly quenching a molten alloy to produce a amorphous metal and then heat treating this alloy at higher than its crystallization temperature The alloy forms Nanocrystalline grain size of approximately 10 nm in the amorphous metal. BH loops are modified by annealing with magnetic fields oriented either parallel or perpendicular to the ribbons surface.
**Ferrite Cores**

- Ferrite is a class of ceramic material with useful electromagnetic properties. It is rigid and brittle. Ferrites consists of a mixture of oxides of metals.
- Ferrite cores are pressed from a powdered precursor and then sintered (fired) in a kiln. The mechanical and electromagnetic properties of the ferrite are heavily affected by the sintering process.
- Ferrite shrinks when sintered. Maintaining correct dimensional tolerances as well as the prevention of cracking and warpage related to this shrinkage are fundamental concerns of the manufacturing process, thus large size cores are not easy to produce.
- Since they have very small eddy current loss, they can be used as solid materials even at high frequencies like 500kHz. The maximum permissible flux density is about 0.3 Wb/sqm.
Skin Effect in Conductors

The current in a conductor tends to crowd around the periphery in ac circuits. Thus, the ratio of ‘ac resistance’ $R_{ac}$ to ‘dc resistance’ $R_{dc}$ for a solid conductor, is higher than unity, the ratio increasing non-linearly with increase in frequency. Thus, in order to keep the ratio near unity, a bundle of wires is to be used instead of a single wire. “Litz wire” is such a wire. Alternatively use thin foils.
Skin Effect in Round Conductors

The ratio of ‘ac resistance’ Rac to ‘dc resistance’ Rdc for a round solid conductor, is expressed by a non-linear relationship with a factor k, where,

\[ k = 1.067 \times 10^{-2} d \sqrt{f} \]

where \( d \) = diameter of conductor in mm
and \( f \) = frequency in Hz

The values of ‘k’ are tabulated against the permitted increase in resistance, from which ‘k’ becomes 1.79 if it is desired to keep the ratio of Rac/Rdc within 5% (ie 1.05). Thus the max diameter is :

\[ d_{\text{max}} = \frac{167.8}{\sqrt{f}} \text{ mm} \]

Thus, individual round conductors must have a diameter less than that calculated above.
Leakage Inductance in Transformers

- Minimum Leakage inductance gives minimum voltage drop with load
- It also generates minimum voltage stress on power semiconductors
- Achieved by very close coupling between windings through Interleaved windings
- Sometimes Leakage inductance is needed
- Minimum Leakage is achieved through minimum turns, higher length of winding

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Inductors in Power Electronics

- Inductors are mostly used in Power Electronics to block the flow of high frequency components of currents.
- Thus, inductors can drop significant amount of high frequency voltages.
- Inductors can have fundamental ac component voltage drop in ac circuits but cannot drop dc component voltages under steady state.
- No inductor is ideal, so their behaviour depends upon the applied frequency.
- The peak flux density depends on the peak instantaneous current.
Theory of Inductors

L = N dΦ/di

\[ \Phi = N \cdot \frac{di}{R} \]

\[ R = \frac{l_c}{\mu_0 \mu_r A_c} + \frac{2l_g}{\mu_0 A_g} \]

Ag = F.Ac

L ≈ \( \mu_0 N^2 F.Ac/2l_g \)
Increased Core loss due to Air Gap

- Amount of Fringing Flux increases with length of Air Gap, hence core loss around air gap increases
- Cores without need for laminations will exhibit small increase in core loss around air gap
Behaviour of Inductor at High Frequency

\[ f_0 = \frac{1}{2\pi \sqrt{L.C}} \]

or Higher C makes Lower \( f_0 \)
Power Frequency Inductors

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High Frequency Inductors

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Speciality in Inductors

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Resistors in Power Electronics

- Resistors are mostly used in Power Electronics to dissipate the trapped energy from other components as well to provide damping
- Thus, resistors can carry significant amount of high frequency currents
- Resistors can carry fundamental ac component currents in ac circuits and also carry dc component currents under steady state
- No resistor is ideal, so their behaviour depends upon the applied frequency
- The peak temperature rise depends on the energy dissipated in the resistors
Behavior of Resistor at High Frequency

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Resistors to be used in parallel to reduce inductance and better cooling through increased surface area.
Capacitors in Power Electronics

- Capacitors are mostly used in Power Electronics to by-pass high frequency components of voltages and currents.
- Thus, capacitors can carry significant amount of high frequency currents.
- Capacitors can carry fundamental ac component currents in ac circuits but cannot carry dc component currents under steady state.
- No capacitor is ideal, so their behaviour depends upon the applied frequency.
- The breakdown voltage depends on the peak voltage charge.
Behavior of Capacitor at High Frequency

\[ Z = \text{ESR} + j\omega \text{ (ESL)} - j\left(\frac{1}{\omega C}\right) \]

- Capacitive
- Inductive

\[ f_0 = \frac{1}{2\pi\sqrt{L.C}} \]

or Higher L makes Lower \( f_0 \)
Use of Paralleled Capacitors of two types

- The 10μF Electrolytic Capacitor has lower capacitive impedance at lower frequency f1.
- However, it behaves as an inductor with increasing impedance at higher frequency f2.
- The 0.1μF Ceramic Capacitor has higher capacitive impedance at lower frequency f1.
- It still behaves as a capacitor with decreasing impedance at higher frequency f2.
Electrolytic Capacitors

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Non - Electrolytic Capacitors
Connection to Capacitors

Incorrect

Correct

Length of leads increases ESL & ESR, making capacitor less effective!
Capacitors in Parallel

Always use capacitors in parallel so that:

- The effective ESR & inductance is reduced
- Ripple current through each capacitor is reduced
- More surface area is available for cooling
Capacitors in Series

Capacitors are needed to be connected in series for higher voltage bus. **However, avoid series connection as far as possible because:**

- The effective ESR & inductance is increased.
- Voltage balancing depends on the tolerance of capacitor values, so sufficient margins in voltage is needed.
- For large bank of capacitor, connect a pair in series and such pairs in parallel. **Do not** connect capacitors in parallel first and then two such banks in series. Failure of one capacitor will cause increased unbalance in capacitor voltage.
Filters in Power Electronics

- Filters are mostly used in Power Electronics to block the flow of high frequency components of voltages and/or currents.
- Thus, filters can drop significant amount of high frequency voltages and carry significant high frequency currents.
- Filters can have fundamental ac component voltage drop in ac circuits but cannot drop dc component voltages under steady state.
- No filter is ideal, so their behaviour depends upon the proper design.
Power Filters

- Frequently used
- Rarely used
- Sometimes used
- Used in specific applications

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Voltage Filters

\[ \frac{v_o}{v_i} = \frac{1}{\omega^2 LC - 1} \]

In AC circuits:
- \( L \) selected from minimum fundamental voltage drop
- \( C \) selected from above equation

In DC circuits:
- \( L \) selected from critical conduction & maximum ripple current
- \( C \) selected on basis of ESR and ripple current handling capability, subject to a minimum value from equations
Current Filters

\[ f_o = \frac{1}{2\pi\sqrt{L_p C_p}} \]

- \( L \) selected from minimum fundamental voltage drop
- \( C_p \) selected from ripple current handling capability for \( i_n \)
- \( L_p \) selected from above equation

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Stray Inductance Problems

\[ V_{sw} = E + L(\frac{di}{dt}) \]
Measurement of Ripple by Oscilloscope Probes
The Interference Problem

• Electro Magnetic Interference (EMI)  
  (Old terminology Radio Frequency Interference or RFI)
• Electro Magnetic Capability (EMC)
• Noise
• Interference
• Susceptibility (also known as Electro Magnetic Vulnerability or EMV)
Generation of Noise in Converter Circuits

- Switching of Currents by Semiconductor Switches
- Large $dv/dt$
- Reverse Recovery Effect in Diodes
- Stray Magnetic Fields from Transformers and Inductors
Modes of Noise Coupling

- Conductive Coupling
- Coupling through Common Impedance
- Capacitive Coupling
- Electric and Magnetic Fields (Radiated)
Types of Noise Currents

1) Differential Mode Noise

2) Common Mode Noise
Noise Sources in Power Converters

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Noise Sources in Power Converters

Parasitic Capacitors of a Transformer
Methods of Reducing Interference

- Use twisted wires or closely placed bus bars pairs
- Reduce physical distance between the switching element and the nearest capacitor coming across the lines
- Use suitable shielding for radiated noise
- Use large ground areas on PCB
- Use appropriate types of capacitors
- Use shields in magnetic components with appropriate placement of windings
- Use appropriate layout of components
Shielding in Transformers

Dirty power with noise and spikes into the shielded transformer

Shielded transformer

Clean power out of the shielded transformer

With Faraday Shield

Without Faraday Shield

www.interfacebus.com
Filters for Reducing Conducted Noise Propagation

Integrated Magnetic Structure in a Common Mode Filter Choke

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EMI Problem due to bad Layout

Switching Circuit

DC Bus Cap

Rectifier

Filter for EMI

AC Mains

Radiated

Output DC

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CASE STUDY – 1:
Non-isolated inverter for Railway Coach: 10kVA

Option #1

110V I/P → PWM Inverter → Transformer → Filter → 230V O/P

Option #2

110V I/P → Boost Converter → Inductor & Capacitor → PWM Inverter → Filter → 230V O/P

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CASE STUDY – 2:
Sine Wave Inverter

Option #1

DC to DC Converter → Rectifier & Filter → PWM Inverter

Option #2

PWM Inverter → Transformer
Fuel Pump Motor with built-in Inverter

Features:
- More reliable than DC Motors
- No Maintenance
- Fully microcontroller-based compact design
- One compact unit of AC motor with built-in inverter
- Easy interchangeability with existing DC motors
- Can fit easily with existing systems
- Accept wide range swing in input voltage from 20V to 80V DC
- Constant torque with v/f control
- Reverse Polarity protection in the input side of the inverter
DSP controlled IGBT based
35kW Battery Charger

Features:
- DSP controlled IGBT based front-end converter with active power factor correction.
- PWM controlled high frequency full bridge isolated DC-DC converter in 2nd stage.
- Wide input 3-phase AC voltage (50Hz / 60Hz) range from 350V - 480V.
- Extensive output DC voltage range upto 155 VDC.
- Output DC current upto 220A.
- Regulation within ±1%.
- Efficiency > 91%.
- Near Unity power factor.
- THD <= 5% for both input voltage and current.
- Low weight and compact size in comparison with SCR based chargers
- Overload and short-circuit protected.
- Rolling-stock application.
Ground Power Units (GPU) for Aircraft Starting & Testing

Features:
- Can be driven along tarmac to aircraft
- Diesel engine driven alternator for 400Hz supply
- Battery backup
- 28V dc supply at 1000A for engine starting
Submarine Battery Chargers

Features:
- Can be driven upto sea shore
- Upto 380V, 4000A output
- Can operate at hostile marine weather
- Uses two rectifiers in parallel current sharing mode, each with 12 pulse output
Thank you for your patient hearing.