Cheat Sheet for EE463

Performance Parameters

$$I_{rms} = \sqrt{\frac{1}{T}\int i^2 dt}$$

$$CrestFactor = \frac{V_{peak}}{V_{rms}}$$

$$DistortionFactor = \frac{I_{1rms}}{I_{rms}} = \frac{1}{\sqrt{1+THD^2}}$$

ϕ : phase difference between fundamentals of current and voltage

$$DisplacementPowerFactor = \cos(\phi)$$

$$TruePowerFactor = \frac{P}{S} = DPF\frac{I_{1,RMS}}{I_{RMS}}$$

$$THD = \sqrt{(\frac{I_{rms}}{I_{1rms}})^2 - 1}$$

Single Phase Diode Rectifier

$$V_{av} = \frac{2\sqrt{2}V_s}{\pi}(Fullwave), V_{av} = \frac{\sqrt{2}V_s}{\pi}(Halfwave)$$

u: commutation period

$$\cos(u) = 1 - \frac{2\omega L_s I_d}{\sqrt{2}V_s} \qquad \text{(Full wave)}$$

$$\cos(u) = 1 - \frac{\omega L_s I_d}{\sqrt{2}V_s} \qquad \text{(Half wave)}$$

$$A_u = \int_0^u V_s\sqrt{2}sin(\omega t)d\omega t = \omega L_s I_d$$

$$\text{Commutation Loss : } \frac{2\omega L_s I_d}{2\pi} \qquad \text{(Full wave)}$$

$$\frac{\omega L_s I_d}{2\pi} \qquad \text{(Half wave)}$$

$$I_{d,avg} = \frac{\int_b^f i(\theta)d\theta}{\pi}$$

$$I_{d,shortcircuit} = \frac{V_s}{\omega L_s}$$

Three Phase Rectifier

- Half Wave

$$V_{av} = \frac{3\sqrt{6}V_s}{2\pi} = \frac{3\sqrt{2}V_{ll}}{2\pi}$$

- Full Wave

Full Bridge Rectifier Average Output V_s:rms value of source voltage

$$V_{av} = \frac{3\sqrt{6}V_s}{\pi} - \frac{3wL_sI_d}{\pi}$$

Pros / cons of Ćuk:

✓ input-output currents ripple free (no sharp edges)
✓ lower filtering requirements
✓ ≈ Constant source current
✗ C1 bulky, needs large ripple current rating
✗ Complex circuit

Comparison of Rectifiers

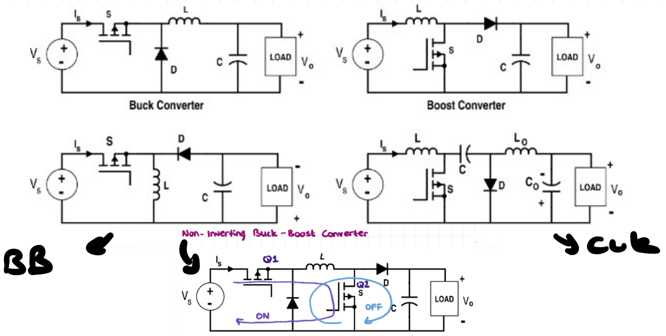
Type	Vout	ΔVout	f_{ripple}
Single Phase	$\frac{2\sqrt{2}}{\pi}V_{ph}$ = 207 V	$\sqrt{2}V_{ph} = 325V$	100 Hz
3-phase Half Bridge	$\frac{3\sqrt{2}}{2\pi}V_{l-l}$ = 270 V	$\frac{\sqrt{2}}{2}V_{ph} = 162.5V$	150 Hz
3-phase Full Bridge	$\frac{3\sqrt{2}}{\pi}V_{l-l}$ = 540 V	$(1-\frac{\sqrt{3}}{2})\sqrt{2}V_{l-l} = 75.8V$	300 Hz

Voltage Ripple of Buck Converters

$$\Delta Q = \frac{\frac{\Delta I_L}{2}\cdot\frac{T_s}{2}}{2} = \frac{T_s\Delta I_L}{8} \qquad \Delta V_o = \frac{\Delta Q}{C} \Rightarrow \Delta V_o = \frac{T_s\Delta I_L}{8C}$$

using off-time (1-D) & $I_L = \frac{1}{L}\int V_L dt$ $\Rightarrow \Delta I_L = \frac{V_o(1-D)T_s}{L} \Rightarrow \Delta V_o = \frac{T_s V_o(1-D)T_s}{8LC} \Rightarrow \boxed{\frac{\Delta V_o}{V_o} = \frac{(1-D)T_s^2}{8LC}}$

$$T_s = \frac{1}{f_s}, \quad f_c = \frac{1}{2\pi\sqrt{LC}} \Rightarrow LC = \frac{1}{4\pi^2 f_c^2} \rightarrow \frac{\Delta V_o}{V_o} = \frac{(1-D)\cdot 4\pi^2 f_c^2}{8 f_s^2} \Rightarrow \boxed{\frac{\Delta V_o}{V_o} = \frac{(1-D)\pi^2}{2}\left(\frac{f_c}{f_s}\right)^2}$$



Buck Converter (Step-Down)

$$\text{Gain: } V_o = DV_d$$

$$V_L = V_d - V_o \text{ (On)}, \quad V_L = -V_o \text{ (Off)}$$

$$\text{Inductor Ripple: } \Delta I_L = \frac{V_o(1-D)}{Lf_s}$$

$$\text{Voltage Ripple: } \frac{\Delta V_o}{V_o} = \frac{1-D}{8LCf_s^2}$$

$$\text{CCM/DCM Boundary: } I_{LB} = \frac{\Delta I_L}{2} = \frac{DT_s(V_d)(1-D)}{2L}$$

$$\text{CCM/DCM Boundary: } L_{min} = \frac{DT_s(V_d - V_o)}{2I_{LB}} = \frac{RT_s(1-D)}{2}$$

Boost Converter (Step-Up)

$$\text{Gain: } V_o = \frac{V_d}{1-D}$$

$$V_L = V_d \text{ (On)}, \quad V_L = V_d - V_o \text{ (Off)}$$

$$\text{Inductor Ripple: } \Delta I_L = \frac{V_d D}{Lf_s}$$

$$\text{Voltage Ripple: } \frac{\Delta V_o}{V_o} = \frac{D}{RCf_s}$$

$$\text{CCM/DCM Boundary: } I_{LB} = \frac{\Delta I_L}{2} = \frac{V_d DT_s}{2L}$$

$$\text{Min Inductance: } L_{min} = \frac{D(1-D)^2 R}{2f_s}$$

Buck-Boost Converter

$$\text{Gain: } V_o = V_d\frac{D}{1-D}$$

$$V_L = V_d \text{ (On)}, \quad V_L = -V_o \text{(Off)}$$

$$\text{Inductor Ripple: } \Delta I_L = \frac{V_d D}{Lf_s}$$

$$\text{Voltage Ripple: } \frac{\Delta V_o}{V_o} = \frac{D}{RCf_s}$$

$$\text{CCM/DCM Boundary: } I_{LB} = \frac{\Delta I_L}{2} = \frac{V_d DT_s}{2L}$$

$$\text{Min Inductance: } L_{min} = \frac{(1-D)^2 R}{2f_s}$$

Cuk Converter

$$\text{Gain: } V_o = -V_d\frac{D}{1-D}$$

$$V_{L1} = V_d \text{ (On)}, \quad V_{L1} = V_d - V_{C1} \text{ (Off)}$$

$$\text{Inductor Ripple } (L_1)\text{: } \Delta I_{L1} = \frac{V_d D}{L_1 f_s}$$

$$\text{Inductor Ripple } (L_2)\text{: } \Delta I_{L2} = \frac{V_d D}{L_2 f_s}$$

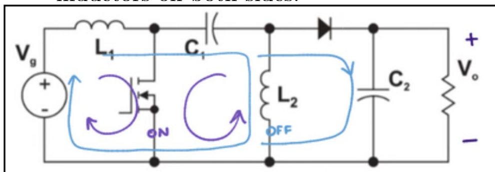
$$\text{Voltage Ripple } (C_o)\text{: } \frac{\Delta V_o}{V_o} = \frac{1-D}{8L_2C_2f_s^2}$$

$$\text{CCM/DCM Boundary: } I_{LB1} = \frac{V_d DT_s}{2L_1} \quad (\text{for } L_1)$$

$$\text{Min Inductance } (L_1)\text{: } L_{1,min} = \frac{(1-D)^2 R}{2Df_s}$$

$$\text{Min Inductance } (L_2)\text{: } L_{2,min} = \frac{(1-D)R}{2f_s}$$

Cuk Feature: Input and Output currents are continuous (low ripple) due to inductors on both sides.



Can be used both as a buck or a boost converter

Popular in battery powered systems

Can be shut down completely

SEPIC CONVERTER
(single ended primary inductor conv.)

ON State

$V_{L_1} = V_s$, $V_{L_2} = V_{C_1} = V_s$

$-V_s + V_{L1} + V_{C1} - V_{L2} = 0$

in steady state: $V_{L1} = V_{L2} = 0$

assume C_1 large enough $\Rightarrow V_{C1}$ const

$\Big\}\ V_{C1} = V_s$

OFF state

$-V_s + V_{L1} + V_{C1} + V_o = 0$

$V_{C1} \cong V_s \Rightarrow V_{L1} = -V_o$

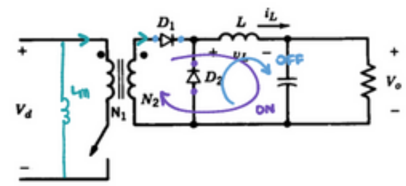
$V_s \cdot D \cdot T_s + (-V_o)(1-D)T_s = 0 \Rightarrow \boxed{V_o = V_s \cdot \frac{D}{1-D}}$

Pros / Cons of SEPIC :

✓ Functions as non-inverting buck-boost
✓ Efficient as can be completely turned off
✓ Inductors can be combined to a single core
✓ Smaller inductance requirement

✗ Pulsating output current
✗ Large capacitance & ripple current rating required
✗ 4th order TF: difficult to control

FORWARD CONVERTER

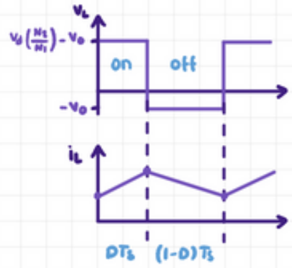


ON State

$$V_L = V_d \cdot \left(\frac{N_2}{N_1}\right) - V_o$$

OFF State

$$V_L = -V_o$$



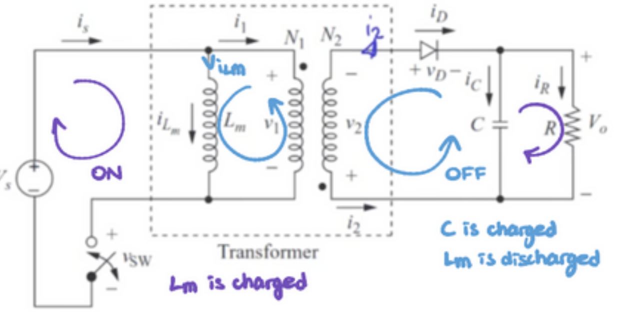
$$\left(V_d\left(\frac{N_2}{N_1}\right) - V_o\right) D = V_o(1-D)$$

$$V_d \cdot \frac{N_2}{N_1} \cdot D - V_o D = V_o - V_o D$$

$$\boxed{V_o = V_d \frac{N_2}{N_1} D}$$

Like a buck converter with added turns ratio

The energy stored in Lm, if discharged through the switch, could destroy the MOSFET. To prevent this, a snubber circuitry could be added but would cause important losses.
A practical solution is to add an extra winding:



FLYBACK CONVERTER

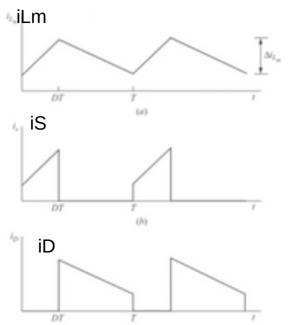
ON State

Diode is reverse biased, hence OFF
⇒ $i_2 = 0$ ⇒ $i_4 = 0$
⇒ transformer acts as a mere inductor
Lm is charging (as in buck-boost)

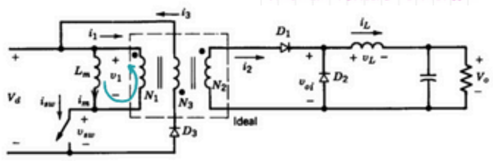
$$V_{Lm} = V_s$$

OFF State

$$V_{sw} = V_s + V_o\left(\frac{N_1}{N_2}\right)$$



Practical Forward Converter:



With this implementation, the energy stored in Lm is discharged to the source.

$$i_1 = -i_{Lm}$$

$$N_1 i_1 = N_2 i_2 - N_3 i_3$$

$$N_1 i_1 = -N_3 i_3$$

$$(L_m)_{min} = \frac{(1-D)^2 R}{2f} \cdot \left(\frac{N_1}{N_2}\right)^2$$

Transformer Reset:	$t_m < (1-D)T_s$
Max Duty Cycle:	$D_{max} = \frac{1}{1 + (N_3/N_1)}$

ON State

$V_1 = V_s$

$V_2 = V_1 \frac{N_2}{N_1} = V_s \frac{N_2}{N_1}$

$V_3 = V_1 \frac{N_3}{N_1} = V_s \frac{N_3}{N_1}$

$V_{D3} = -V_s - V_3 < 0$ ⇒ D_3 is off

$V_{Lm} = V_s \qquad \Delta i_{Lm} = \frac{V_s D T_s}{L_m}$

$i_{sw} = i_1 + i_{Lm}$

OFF State

$i_{Lm} = -i_1$

$V_3 = -V_s$

$V_1 = V_3 \cdot \frac{N_1}{N_3} = -V_s \frac{N_1}{N_3}$

$V_2 = V_3 \cdot \frac{N_2}{N_3} = -V_s \cdot \frac{N_2}{N_3}$

$N_1 i_1 = N_2 i_2 - N_3 i_3 \qquad N_1 i_1 = -N_3 i_3$

$i_3 = \frac{-N_1}{N_3} i_1$

$V_{Lm} = V_1 = -V_s \frac{N_1}{N_3} = L_m \frac{di_{Lm}}{dt}$

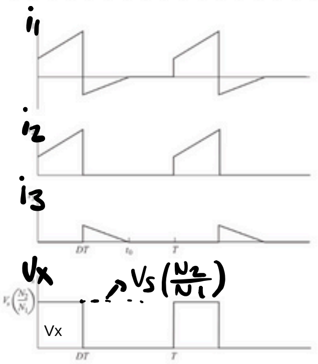
$\frac{di_{Lm}}{dt} = \frac{-V_s}{L_m} \cdot \frac{N_1}{N_3}$

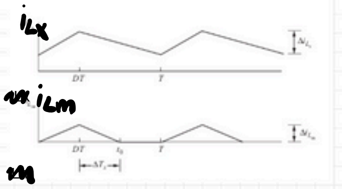
There are multiple ways to calculate the voltage relations of a flyback. It can be done using:

- transformer flux
- steady state current
- voltage-seconds balance

FLYBACK CONVERTER

Gain:	$V_o = V_d \frac{N_2}{N_1} \frac{D}{1-D}$
Inductor Voltage:	$V_L = Vd$ (On), $\quad V_L = -\frac{N_1}{N_2} V_o$ (Off)
Inductor Ripple:	$\Delta I_L = \frac{N_1}{L_m N_2}(1-D)V_o$
Voltage Ripple:	$\frac{\Delta V_o}{V_o} = \frac{N_1}{8 f_s C L_m N_2}(1-D)$
CCM/DCM Boundary:	$I_{LB} = \frac{\Delta I_L}{2} = \frac{(1-D)V_o T_s N_1}{2 L_m N_2}$





$\Delta T_x < (1-D)T_s$

$$i_{Lm(max)} = \frac{V_s D T_s}{L_m} = \frac{V_s \cdot D \cdot T_s}{L_m}$$

$$\Delta T_x = \frac{\frac{V_s D T_s}{L_m}}{\frac{V_s}{L_m} \cdot \frac{N_1}{N_3}} = D \cdot T_s \cdot \frac{N_3}{N_1}$$

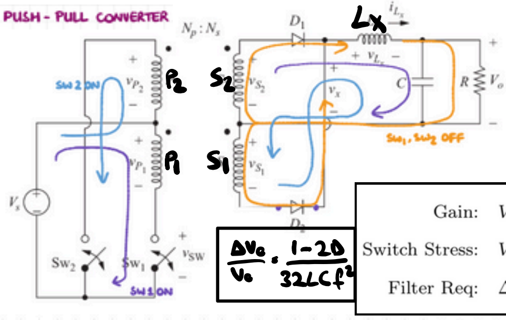
$$\Delta T_x = D T_s \frac{N_3}{N_1} < (1-D)T_s$$

$D\left(1 + \frac{N_3}{N_1}\right) < 1$

usually, $N_1 = N_3$

⇒ $\boxed{D < 0{,}5}$

PUSH-PULL CONVERTER



The design uses a center-tap transformer (turns ratio can be adjusted)

The converter has 3 operating regions:

$$\frac{\Delta V_o}{V_o} = \frac{1-2D}{32 L C f^2}$$

Gain:	$V_o = 2V_d \frac{N_2}{N_1} D$	
Switch Stress:	$V_{sw} = 2V_d$	
Filter Req:	$\Delta I_L = \frac{V_o(0.5-D)}{Lf_s}$	(for $D < 0.5$)

SW1 ON, SW2 OFF

D_1 conducts, D_2 reverse biased

$V_L = V_x - V_o = \frac{N_2}{N_1} V_s - V_o$

i_L increases linearly

SW2 ON, SW1 OFF

Symmetrical operation

$V_L = V_x - V_o = \frac{N_2}{N_1} V_s - V_o$

i_L increases linearly

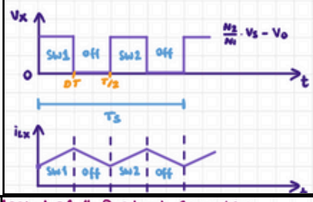
Both Switches OFF

For a period Δ, D_1 & D_2 conduct

$I_{D_1} = I_{D_2} = 0{,}5\, I_L$

$V_x = 0$ ⇒ $V_L = -V_o$

inductor feeds the load



Waveform is repeating every $T_s/2$

$DT_s + \Delta = T_s/2$

$\Delta = \frac{(1-2D)}{2} T_s$

$$\boxed{\frac{V_o}{V_d} = 2\frac{N_2}{N_1} D}$$

Advantages / Disadvantages:

✓ Better usage of the core compared to Forward conv.
✓ Better B-H curve: uses both +/- regions
✗ Need to control 2 switches

Advantages / Disadvantages over Flyback

✓ Better use of transformer (direct & higher power transfer)
✓ Gapless core can be used (higher Lm → less ripple)
✓ Output inductor + diode ensure continuous output current

Practical Forward Converter:

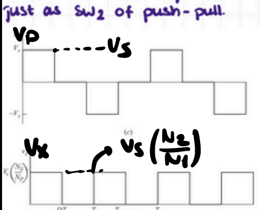
✗ Possibly increased cost
✗ Gain changes a lot in DCM & may require closed-loop control
✗ Higher voltage requirement for MOSFET

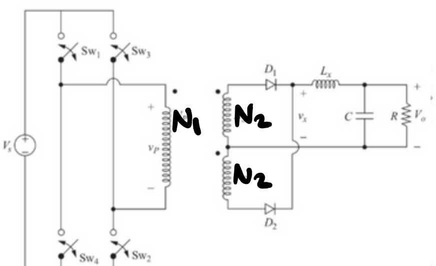
FULL BRIDGE ISOLATING CONVERTER

Operation very similar to push-pull conv.

Switches 1 & 2 are operated together just as SW1 of push-pull.

Switches 3 & 4 are operated together just as SW2 of push-pull.

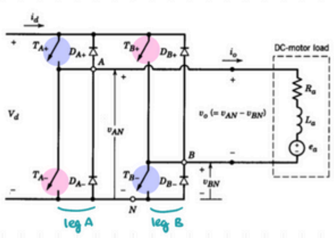




$$\boxed{V_o = 2V_s \frac{N_2}{N_1} D}$$

$D < 0{,}5$

Control of 4 Quadrant Converters



Bipolar Voltage Switching

T_{A+} & T_{B-} are ON or OFF together

T_{A-} & T_{B+} are complimentary to T_{A+}, T_{B-}

Output can be $+V_d$ or $-V_d$

Average output according to switch durations

Uni-Polar Voltage Switching

T_{A+} & T_{B+} controlled seperately

T_{A-} & T_{B-} complimentary of T_{A+}, T_{B+}

Output can be $+V_d$, 0, $-V_d$

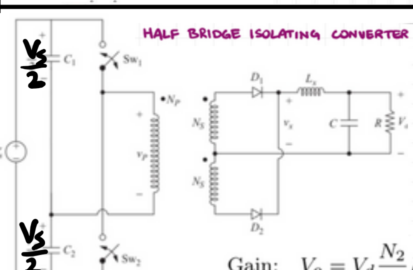
$V_o = 0$ if two (+) OR two (−) are ON

The output relation is the same in both cases:

$$V_o = V_d \frac{V_{control}}{\hat{V}_{tri}}$$

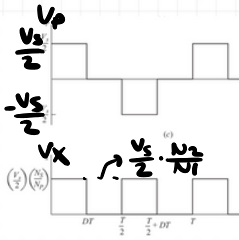
However, the ripple is lower & efficiency is higher in the uni-polar case as the voltage level does not have to be negative to decrease the average; instead it can be zero (0).

HALF BRIDGE ISOLATING CONVERTER



Gain: $V_o = V_d \frac{N_2}{N_1} D$

Very similar to full-wave converter.
Less switches are used: output voltage halved



MAGNETIC DESIGN

For the same flux density, more energy can be stored with a material of lower permeability (μ).
When designing a core, air gaps can intentionally be added to increase the energy storage capacity.

Ferrite vs Powder Cores

Ferrite cores have sharp, powder cores have soft saturation
Powder cores are usually smaller
Powder cores' magnetic properties are less dependent on temperature
Powder cores have higher inductance tolerances

$R = \frac{l}{\mu A}$

$L = N^2/R$

Magnetics & Energy

- **Magnetic Circuit:**

$$\mathcal{F} = N \cdot i = \phi \cdot \mathcal{R}, \quad \phi = B \cdot A$$

- **Reluctance:**

$$\mathcal{R} = \frac{l}{\mu A} = \frac{l}{\mu_r \mu_0 A}$$

- **Inductance:**

$$L = \frac{N^2}{\mathcal{R}} = \frac{N\phi}{i} = \frac{N^2 \mu A}{l}$$

- **Energy Storage:**

$$W = \frac{1}{2}Li^2 = \frac{1}{2}\mathcal{R}\phi^2, \quad w_{density} = \frac{B^2}{2\mu}$$

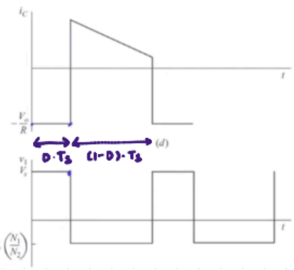
- **Faraday's Law:**

$$v = N\frac{d\phi}{dt} = L\frac{di}{dt}$$

$$\Delta B = \frac{L \cdot \Delta I}{N \cdot A_e}$$

- **True:** Push-Pull converters utilize the transformer core more efficiently than Forward converters.
  - **Reason:** They operate in two quadrants (1st and 3rd) of the B-H curve, driving the flux in both positive and negative directions. This doubles the usable flux swing compared to a Forward converter, which only uses one quadrant. +1

Volt-seconds method:



Flyback

$$V_s \cdot DT_s - V_o \frac{N_1}{N_2}(1-D)T_s = 0$$

$$V_s D = V_o \frac{N_1}{N_2}(1-D)$$

$$\boxed{\frac{V_o}{V_s} = \frac{D}{1-D} \cdot \frac{N_2}{N_1}}$$

buck-boost

transformer ratio also controls V_o

$$\boxed{\begin{aligned} \Delta i_{L_m} &= \frac{V_s D T_s}{L_m} \\ \Delta V_o &= \frac{i_o \cdot DT_s}{C} \end{aligned}}$$

In DCM:

$$i_{L_m,max} = \frac{V_s D T_s}{L_m}, \quad i_{s_{on}} = \frac{1}{2} i_{Lmax} \cdot D$$

$$P_{in} = I_{s_{on}} \cdot V_s = P_{out} = \frac{V_o^2}{R_L}$$

$$\boxed{\frac{V_o^2}{R_L} = \frac{1}{2}\frac{V_s D T_s}{L_m} \cdot D \cdot V_s}$$

Magnetic flux method

ON state

$$V_1 = N_1 \cdot \frac{d\phi}{dt} \text{ : ON period} \Rightarrow V_s = N_1 \cdot \frac{d\phi}{dt}$$

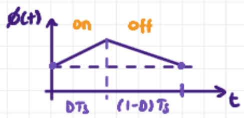
$$\Rightarrow \Delta\phi = \frac{V_s \cdot \Delta t}{N_1}$$

$$\phi(t) = \phi(0) + \frac{V_s}{N_1} \cdot t \Rightarrow \phi(DT_s) = \underbrace{\phi(0) + \frac{V_s}{N_1} \cdot DT_s}_{\text{peak flux}}$$

OFF state

$$V_2 = N_2 \cdot \frac{d\phi}{dt} \text{ : OFF period}$$

$$\phi(T_s) = \hat{\phi}_{core} - \frac{V_o}{N_2}(1-D)T_s = \phi(0)$$



$$\phi(0) + \frac{V_s}{N_1} DT_s - \frac{V_o}{N_2}(1-D)T_s = \phi(0)$$

$$\frac{V_s}{N_1} \cdot D = \frac{V_o}{N_2}(1-D) \Rightarrow \boxed{\frac{V_o}{V_s} = \frac{D}{1-D} \cdot \frac{N_2}{N_1}}$$

Switch Selection

$$I_{sw} = \frac{1}{1-D} \cdot \frac{N_2}{N_1} \cdot I_o + \frac{N_1}{N_2} \cdot \frac{(1-D)T_s}{2L_m} \cdot V_o \quad \text{: peak switch current}$$

$$V_{sw} = V_d + \frac{N_1}{N_2} V_o = \frac{V_d}{1-D} \quad \text{: peak switch voltage}$$

- **True:** The Displacement Power Factor (DPF) is different from the True Power Factor (PF) in non-linear circuits.
  - **Reason:** DPF only considers the phase difference between the **fundamental** voltage and current ($DPF = \cos\phi_1$). True PF includes the effect of **harmonics** (Distortion Factor), calculated as $PF = DPF \times DF$. +1
- **True:** A perfect square wave has a Distortion Factor (DF) less than 1 (approx 0.9).
  - **Reason:** A square wave is composed of the fundamental frequency plus many higher-order harmonics. Since DF is the ratio of Fundamental RMS to Total RMS ($\frac{I_{1rms}}{I_{rms}}$), the presence of these harmonics increases the Total RMS, reducing the ratio below 1. +1
- **True:** Total Harmonic Distortion (THD) represents the "purity" of the waveform relative to the fundamental.
  - **Reason:** It is defined as the ratio of the RMS value of all **harmonics** (excluding the fundamental) to the RMS of the **fundamental** component. Higher THD means more power is wasted in harmonics. +1
- **True:** In single-phase rectifiers, the presence of source inductance (L_s) causes a drop in the average DC output voltage.
  - **Reason:** Inductance opposes the change in current ($v = Ldi/dt$). This creates a **commutation overlap period** (u) where multiple diodes conduct simultaneously, effectively shorting the input for a brief moment and reducing the area under the output voltage curve. +2
- **True:** A 3-phase full-bridge rectifier is preferred over a half-wave rectifier for high-power applications.
  - **Reason:** The full-bridge rectifier utilizes both the positive and negative halves of the input waveform, resulting in a higher average output voltage ($1.35V_{LL}$ vs $1.17V_{ph}$) and a much higher ripple frequency (6 pulses per period vs 3), which is easier to filter.
- **True:** Unipolar voltage switching in inverters yields better efficiency than bipolar switching.
  - **Reason:** In unipolar switching, the output voltage switches between $+V_d$ and 0 (or $-V_d$ and 0). By utilizing the "zero" state (freewheeling), the effective switching frequency at the output doubles (reducing ripple), and the voltage steps are smaller, reducing harmonics and losses. +1

- **True:** The Cuk converter provides continuous current at both the input and the output.
  - **Reason:** The topology places an inductor in series with the input (L_1) and another in series with the output (L_2). This results in **ripple-free** (non-pulsating) currents on both sides, unlike Buck (pulsating input) or Boost (pulsating output) converters. +1
- **True:** The Buck-Boost converter produces an inverted output voltage.
  - **Reason:** During the OFF state, the inductor forces current to flow through the diode to the load. To maintain the inductor current direction, the capacitor charges with a polarity opposite to the input voltage. +1
- **True:** The SEPIC converter is often used in battery-powered systems where the battery voltage varies above and below the desired output voltage.
  - **Reason:** It supports both step-up and step-down operations (like Buck-Boost) but has a **non-inverting** output polarity (positive output) and can be completely shut down. +1
- **True:** The Flyback converter does not need a separate output inductor.
  - **Reason:** The transformer in a Flyback acts as a **coupled inductor**. Energy is stored in the magnetizing inductance (L_m) when the switch is ON and released to the secondary capacitor/load when the switch is OFF. +1

True: A standard Forward converter requires a specific mechanism (like a tertiary winding) to reset the transformer core.

- **Reason:** Unlike the Flyback, the Forward converter transfers energy instantly and does not store it in the core. If the magnetizing current (i_{Lm}) is not allowed to discharge (reset) to zero during the OFF time, the core flux will build up ("ratchet") and eventually saturate the transformer. +1

True: The maximum duty cycle of a Forward converter is typically limited to $D < 0.5$.

- **Reason:** To ensure the core resets, the "volt-second" balance requires that the Reset Time be equal to or greater than the ON Time (assuming equal winding turns $N_1 = N_3$). If $D > 0.5$, the core cannot fully discharge flux before the next cycle begins.

- **True:** Adding an air gap to a magnetic core increases its energy storage capability.
  - **Reason:** Energy density is given by $w = B^2/2\mu$. An air gap significantly lowers the effective permeability (μ). For the same saturation flux density (B), a lower μ allows much more energy to be stored. +1

Fourier Series

$$f(x) = a_0 + \sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx)$$

$$a_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(x)dx$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)cos(nx)dx$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)sin(nx)dx$$

Faraday's Law of Induction:

- $V = N\frac{d\phi}{dt}$
- $V = NA_{core}\frac{dB_{ac}}{dt}$
- $V = NA_{core}B_{ac}2\pi f\frac{2}{\pi}$
- $V_{pri}I_{pri} = 4N_{pri}A_{core}B_{ac}fI_{pri}$
- $V_{pri}I_{pri} = 4N_{pri}A_{core}B_{ac}fJ_{rms}A_{copper}$
- $k_{cu} = \frac{2N_{pri}A_{copper}}{A_{window}}$
- $V_{pri}I_{pri} = 4N_{pri}A_{core}B_{ac}fJ_{rms}\frac{k_{cu}A_{window}}{2N_{pri}}$

Area Product Formula:

- $V_{pri}I_{pri} = 2fk_{cu}B_{ac}J_{rms}A_{core}A_{window}$
- $A_{core}A_{window} = \frac{V_{pri}I_{pri}}{2k_{cu}J_{rms}B_{ac}f} = WaAc = \frac{P_oD_{cma}}{K_tB_{max}f}$

- **True:** Forced air convection offers a significantly lower thermal resistance than natural convection.
  - **Reason:** The convection heat transfer coefficient (h) for forced air ($10 - 300W/m^2C$) is much higher than for natural convection ($5 - 10W/m^2C$), meanii heat is removed from the surface much faster.
- **True:** Applying a very thick layer of Thermal Interface Material (TIM) (thermal paste) is worse than a thin layer.
  - **Reason:** Thermal paste has a much lower thermal conductivity than metal. Its purpose is only to fill microscopic air voids; a thick layer adds unnecessary thermal resistance to the path ($R = l/kA$).

- **True:** Litz wire has a lower copper fill factor (k_{cu}) compared to solid round or rectangular wire.
  - **Reason:** Litz wire consists of many individually insulated strands twisted together, creating air gaps and insulation bulk that reduce the ratio of effective copper area to total winding area ($k_{cu} \approx 0.3$ for Litz vs. 0.6 for round).
- **True:** As the frequency of operation increases, the skin depth (δ) of the conductor decreases.
  - **Reason:** The skin depth is inversely proportional to the square root of the frequency ($\delta = \frac{7.5}{\sqrt{f}}$ for Copper at 100°C); higher frequencies force current to the surface, reducing the effective cross-sectional area.
- **True:** Interleaving the primary and secondary windings reduces leakage inductance and proximity effect losses.
  - **Reason:** Interleaving reduces the peak Magnetomotive Force (MMF) between layers and improves the coupling between windings, thereby reducing the leakage flux that does not link both coils.
- **True:** To measure the leakage inductance of a transformer, the secondary winding should be short-circuited.
  - **Reason:** Shorting the secondary winding cancels the mutual flux path, allowing the LCR meter connected to the primary to measure only the inductance caused by the leakage flux. +1
- **True:** The mutual inductance (L_m) can be calculated by measuring the total inductance with coils aiding (L_a) and coils opposing (L_o).
  - **Reason:** The formula is $L_m = (L_a - L_o)/4$. In the aiding configuration, mutual inductance adds to self-inductance; in opposing, it subtracts.
- **True:** In the thermal-electrical analogy, **Temperature** is equivalent to **Voltage**, and **Heat (Power) Flow** is equivalent to **Current**.
  - **Reason:** Just as current flows from high potential to low potential, heat flows from high temperature to low temperature ($P = (T_2 - T_1)/R$). +1
- **True:** Thermal capacitance (Heat Capacity) is neglected during steady-state thermal analysis.
  - **Reason:** Thermal capacitance represents energy storage (like an electrical capacitor). In steady-state (DC conditions), temperatures are constant, so no heat is being stored or released from the thermal mass.
- **True:** A **Black Anodized** aluminum heat sink dissipates heat better by radiation than a **Polished** aluminum heat sink.
  - **Reason:** Black anodized aluminum has a much higher emissivity ($\epsilon \approx 0.86$) compared to polished aluminum ($\epsilon \approx 0.04 - 0.1$), allowing it to radiate more heat energy to the environment.
- **True:** Thermal resistance (R_{TH}) is inversely proportional to the cross-sectional area (A) and thermal conductivity (k).
  - **Reason:** The formula for thermal resistance is $R = \frac{l}{kA}$. Increasing the area or using a material with higher conductivity (like Copper vs. Iron) reduces the resistance to heat flow.