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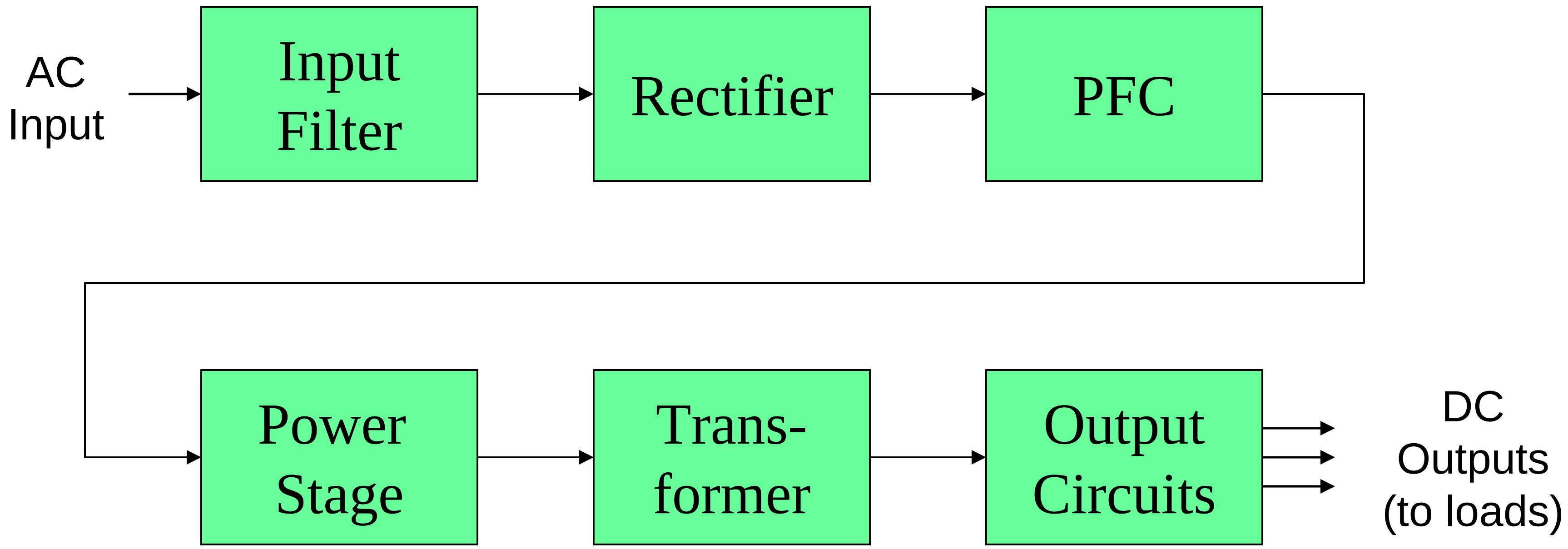
Magnetics in Switched-Mode Power Supplies

Agenda

- Block Diagram of a Typical AC-DC Power Supply
- Key Magnetic Elements in a Power Supply
- Review of Magnetic Concepts
- Magnetic Materials
- Inductors and Transformers

Block Diagram of an AC-DC Power Supply



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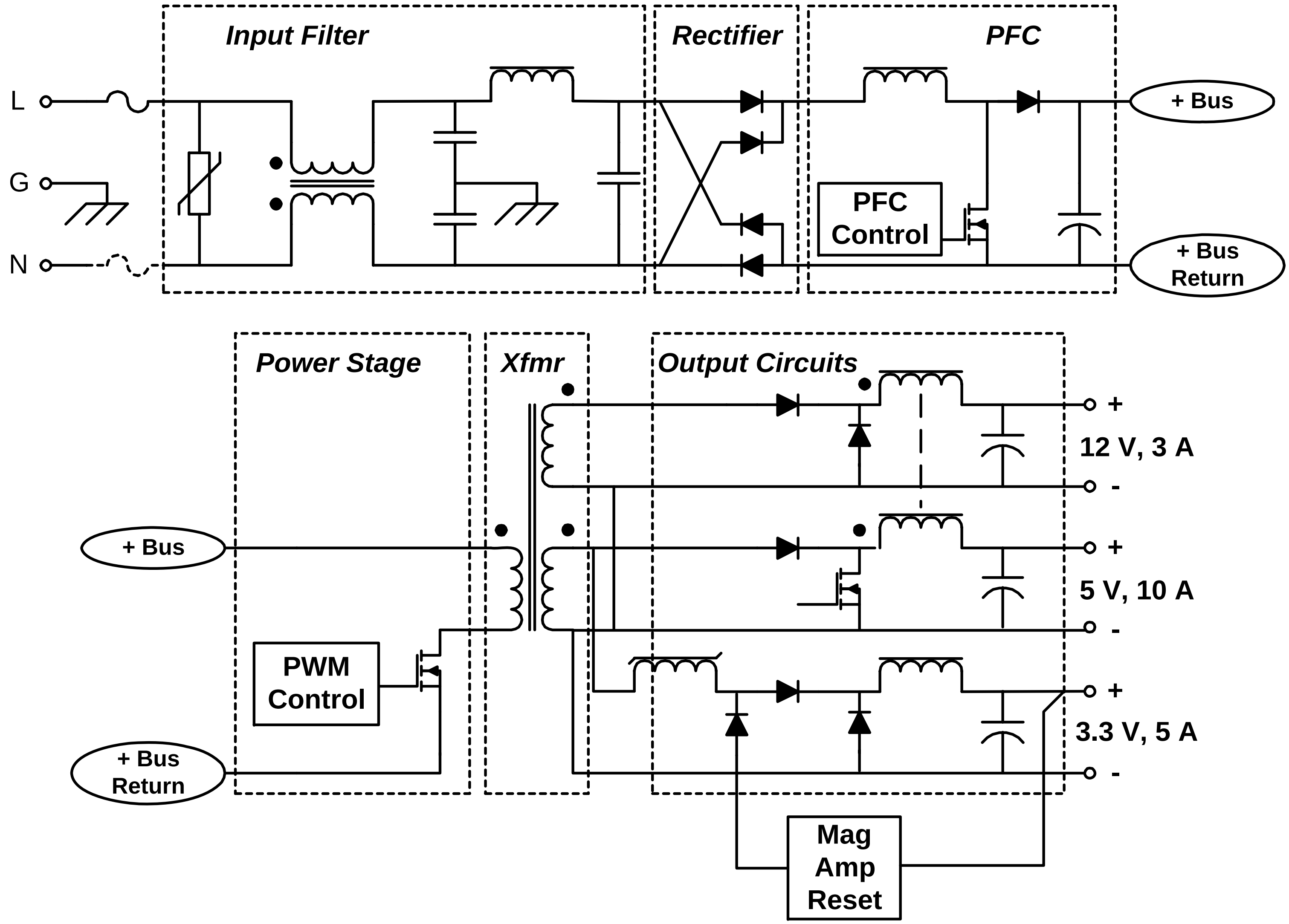
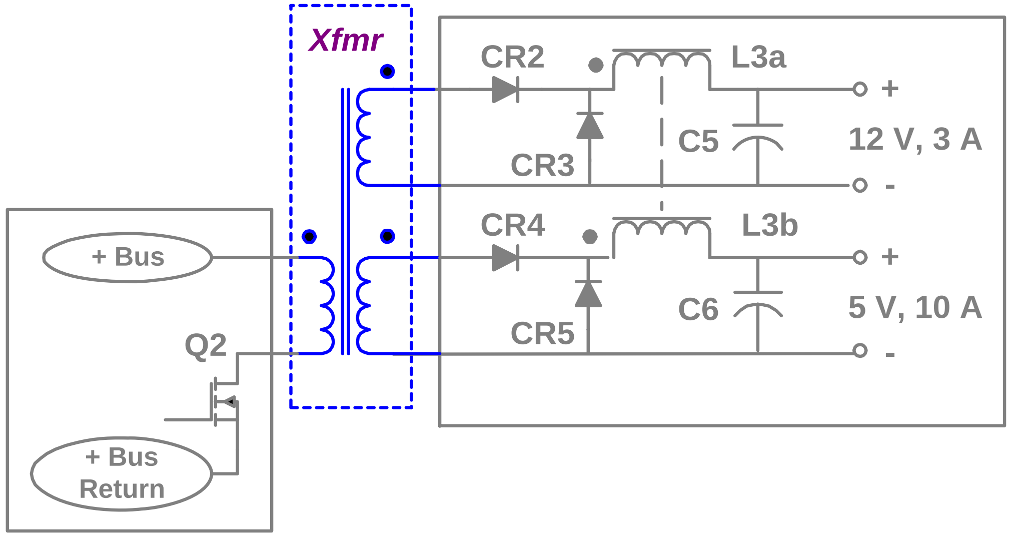
Functional Block Diagram



Transformer



- In forward converters, as in most topologies, the transformer simply transmits energy from primary to secondary, with no intent of energy storage.
- Core area must support the flux, and window area must accommodate the current. => Area product.

$$AP = A_w A_e = \left(\frac{P_O}{K \cdot \Delta B \cdot f} \right)^{\frac{4}{3}} \text{ cm}^4$$

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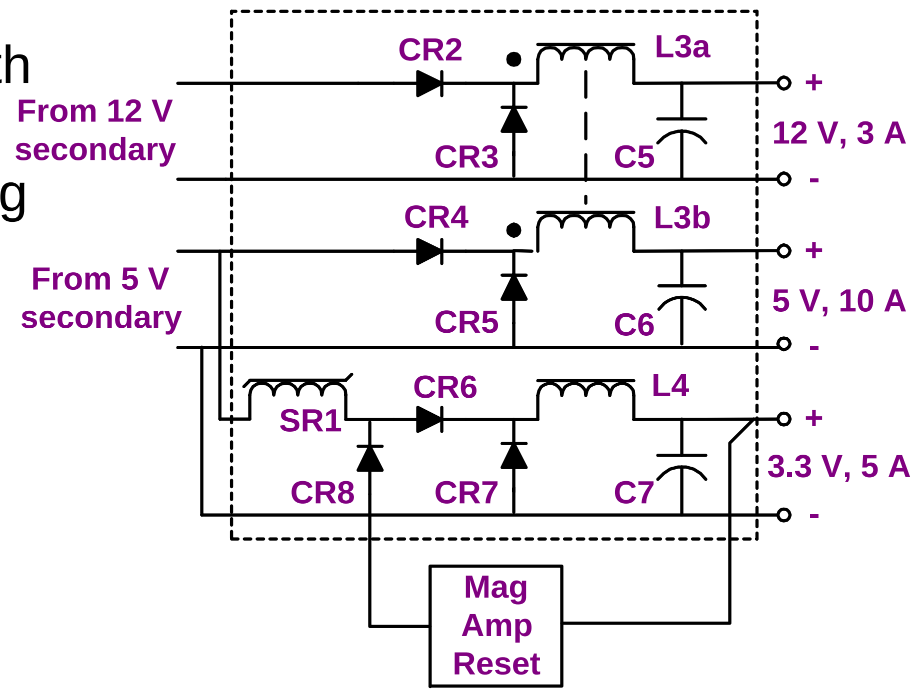
Output Circuits

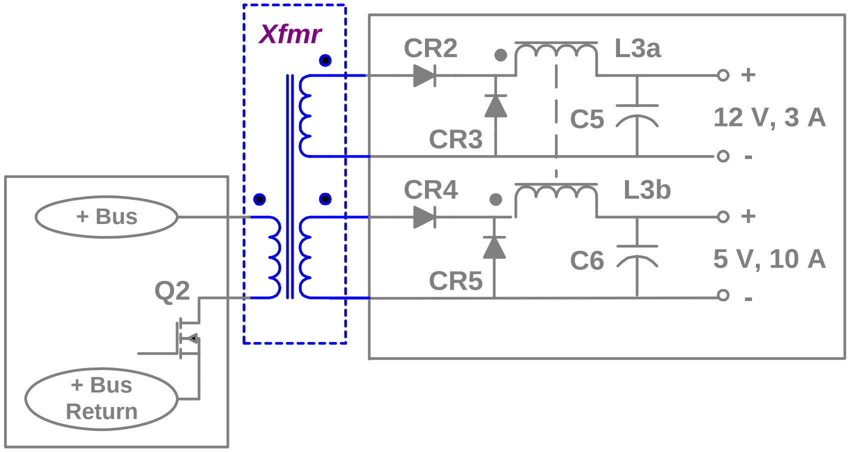
- Popular configuration for these voltages---two secondaries, with a lower voltage output derived from the 5 V output using a mag amp postregulator.



- Feedback to primary PWM is usually from the 5 V output, leaving the +12 V output quasi-regulated.

Transformer (cont'd)

- Note the polarity dots.
  - Outputs conduct while Q2 is on.
  - Secondary Vpeaks = +Bus • Ns/Np
- Note the coupled output choke, L3.
  - Windings must have same turns ratios as transformer, which is the same as output voltages plus diode drops of CR3 and CR5.



- With output chokes in continuous conduction, each output voltage is the average of its secondary voltage (neglecting diode drops).
- Therefore, each output voltage is its secondary peak voltage times the duty ratio of the primary bus voltage, +Bus, (neglecting diode drops and Q2's ON voltage).

Review of Some Magnetic Concepts

- Units used in the design of magnetic components
- Current and magnetic flux
- Characteristics of magnetic materials
- Faraday’s Law (the “transformer equation”)

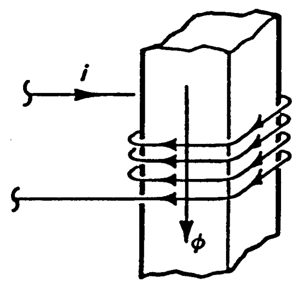
Units and Their Symbols

Symbol	Description	SI Units
H	field strength	A-t/m
B	flux density	tesla (T)
μ	permeability	T-m/A-t^2
F	magnetomotive force	A-t
ϕ	flux	weber/t (Wb/t)
R	reluctance	A-t^2/Wb
P	permeance	henry/t^2
I	current	ampere (A)
L	inductance	henry (H)
N	winding turns	turn (t)

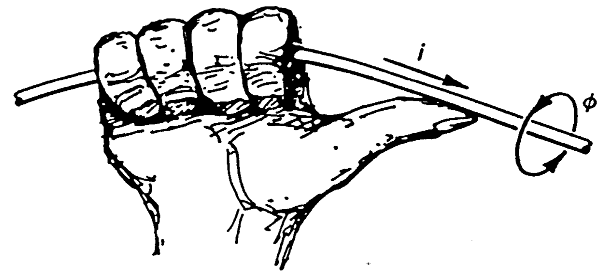
- Units named for famous people are not capitalized (ampere, henry, volt), but their symbols are (A, H, V).
- Always separate the value from the unit symbol (10 uH, not 10uH)---it's not an option.

Right-Hand Rule

Flux Direction as a Result of Current Flow



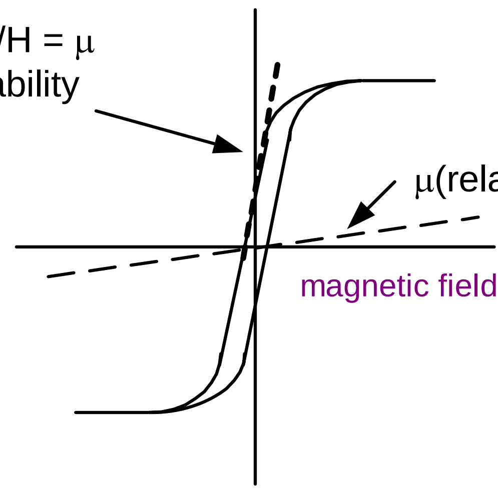
Flux Direction



Right-Hand Rule

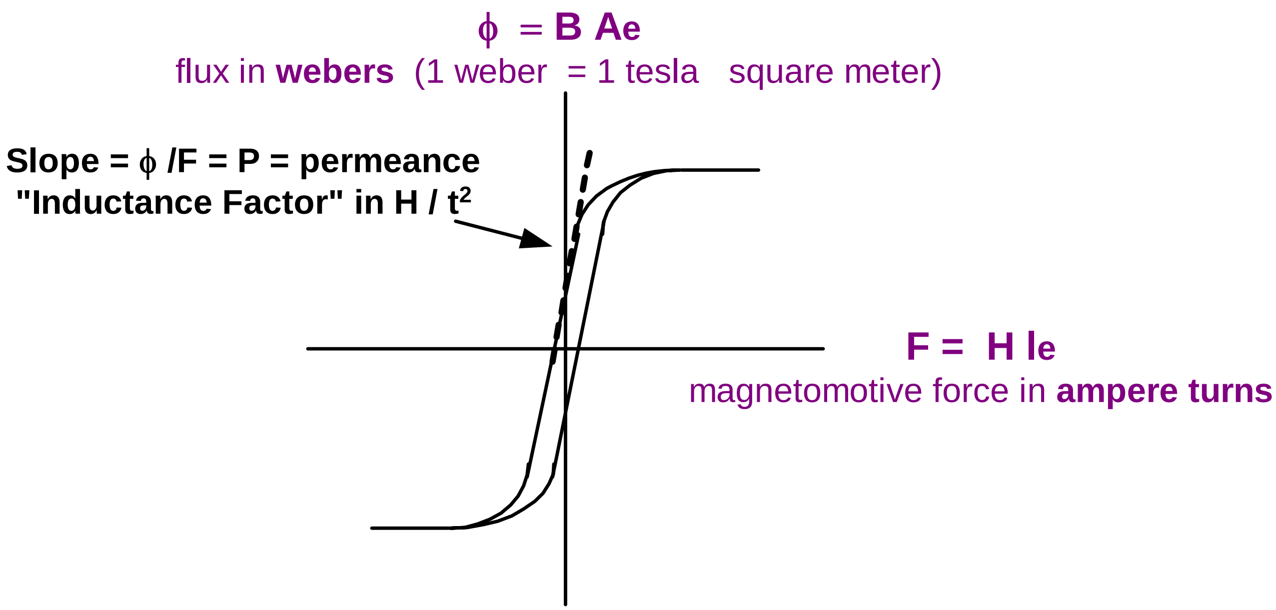
- Wrap one's right hand around a conductor with thumb pointing in the direction of current flow. Fingers point in the direction of flux lines.

Material Characteristics



- Bulk property of the material
- $H = NI/l_e$ = ampere · turns per meter
  - Classic definition is amperes per meter (assumes only one turn)
  - l_e = magnetic path length
- μ = permeability, usually relative to air ($\mu_{air} = 4 \cdot \pi \cdot 10^{-7}$ H/m)

Core Characteristics



- Core with no winding.
- Material characteristics, with A_e and l_e added.
  - A_e = core area, l_e = effective magnetic path length
  - Common unit for the slope is “Inductance Factor,” usually given in nH / t^2

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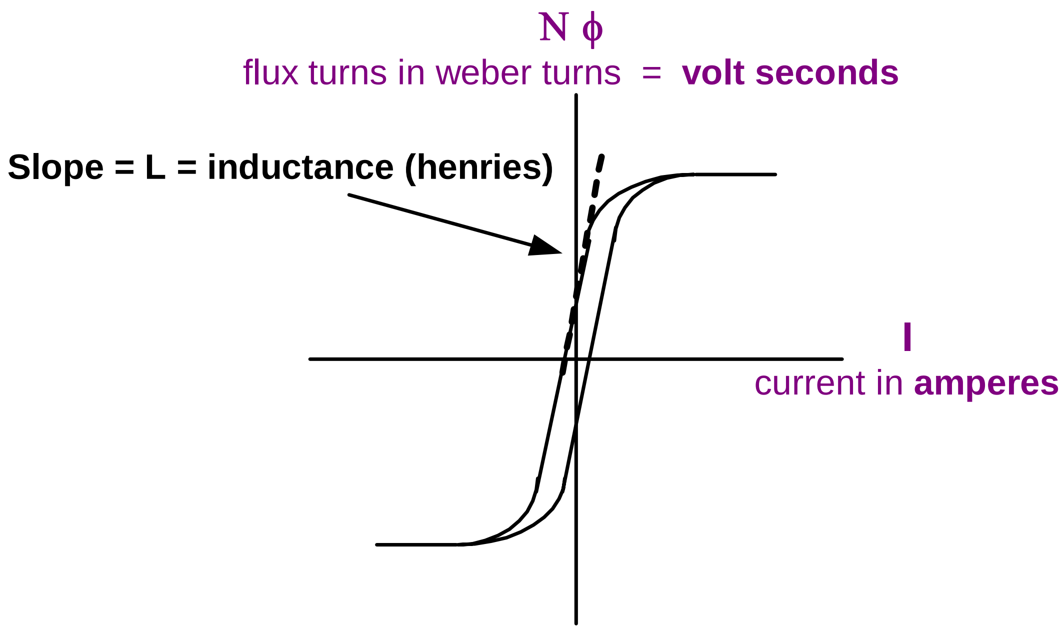
Wound Coil Characteristics



- Using volt-seconds and amperes, the wound component can be analyzed easily by circuit engineers using time-domain analysis.

The “Transformer Equation”
(Faraday’s Law)

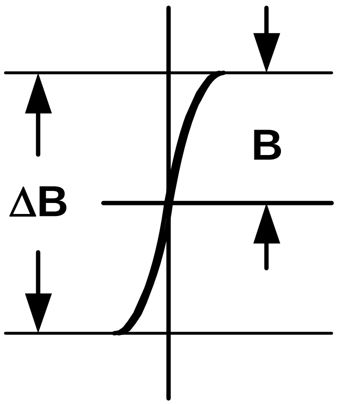
$$\frac{E}{N} = 4B \cdot A_e \cdot f$$

- B in tesla, Ae in m^2, f in Hz
  - Modern SI units
- The saturation flux density, Bmax, determines the maximum volts per turn that can be applied to a given transformer or inductor winding at a given frequency.

Watch closely, now:

Transformer Equation from Faraday's Law

$$E = N\frac{\Delta\Phi}{\Delta t}$$



$$\Phi = B \cdot A_e \qquad \Delta\Phi = \Delta B \cdot A_e = 2B \cdot A_e$$

$$\Delta t = \frac{1}{2}T = \frac{1}{2} \cdot \frac{1}{f}$$

$$\frac{E}{N} = \frac{\Delta\Phi}{\Delta t} = 2B \cdot A_e \cdot \frac{1}{\frac{1}{2f}} = 4B \cdot A_e \cdot f$$

- Note: This applies to square waves (where Δt = half of the period).

An Extremely Important Fact

$$\frac{E}{N} = \frac{\Delta\Phi}{\Delta t} = 4B \cdot A_e \cdot f$$

- Unless the flux is changing, there will be no voltage.
- If the flux swings back and forth, so will the voltage.
- In order for there to be a net dc voltage, the flux must be continually increasing.
- Therefore, our chances of inventing a magnetic rectifier are ZERO.
- The average voltage (dc) across a winding (neglecting winding resistance) is ALWAYS ZERO. This is one of the most useful facts in our bag of tools.

Popular Materials

Material	Permeability (relative)	Bsat (tesla)	Loss @ 0.1 T, 100 kHz (mW/cm3)	Usage
Ferrite (Mag. Inc. P)	2500	0.5	80	Power Transformers Filter Inductors (gapped) PFC Inductors (gapped)
Ferrite (Mag. Inc. W)	10,000	0.42	250	EMI Filters (common-mode only)
Molypermalloy (Mag. Inc. MPP)	60	0.75	340	Filter Inductors PFC Inductors
Sendust (Mag. Inc. Kool-Mu)	60	1	850	Filter Inductors PFC Inductors
Powdered iron (Micrometals 52)	75	1.4	3200	Filter Inductors PFC Inductors
80% Cobalt tape (Honeywell 2714A)	100,000	0.55	90	Mag. Amps

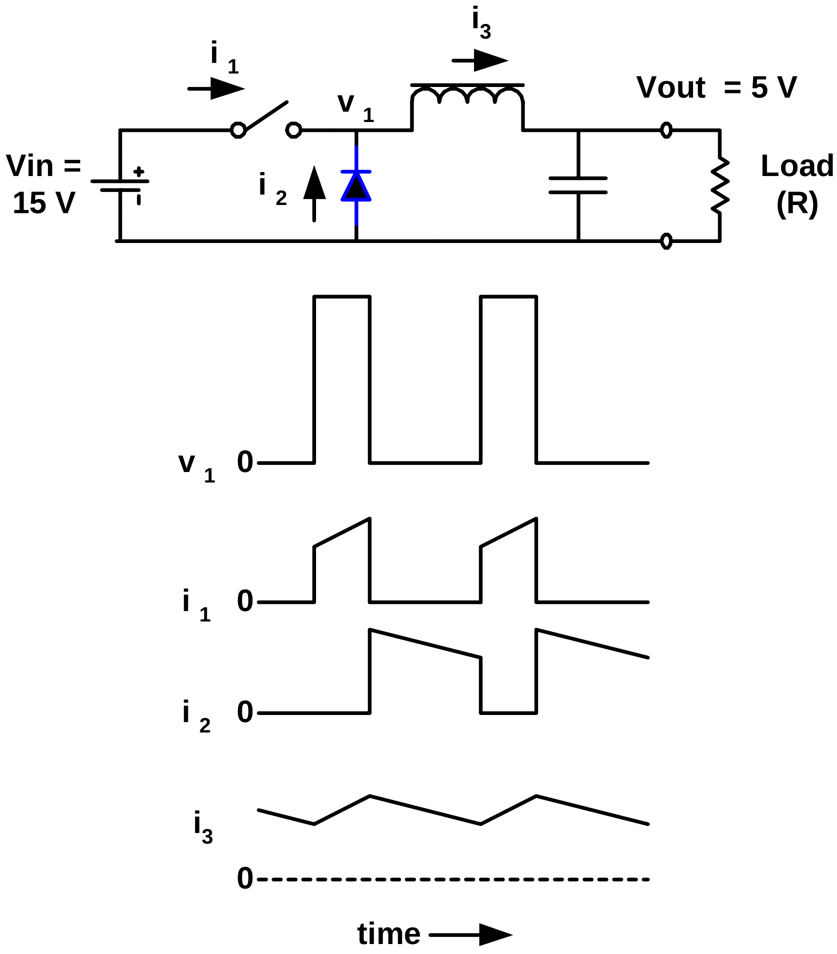
- Note the wide range of permeability and power loss.

Inductors and Transformers

- Inductor operation (example: buck regulator)
- Conduction modes
  - Continuous mode
  - Critical conduction mode
  - Discontinuous mode
- The boost regulator
- Transformer operation
  - Flyback converter
  - Forward converter

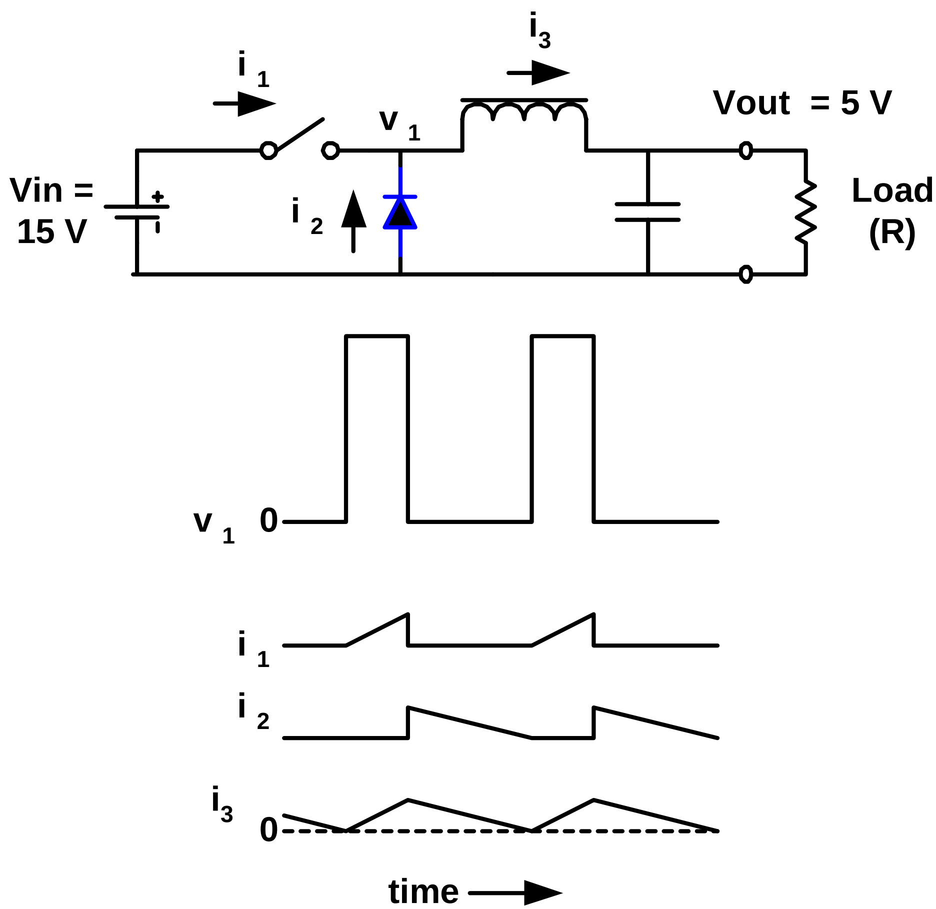
Buck Regulator
(Continuous Conduction)

- Inductor current is continuous.
  - Vout is the average of the voltage at its input (V_1).
  - Output voltage is the input voltage times the duty ratio (D) of the switch.
  - When switch in on, inductor current flows from the battery.
  - When switch is off, it flows through the diode.
  - Neglecting losses in the switches and inductor, D is independent of load current.
- A characteristic of buck regulators and its derivatives:
  - Input current is discontinuous (chopped), and output current is continuous (smooth).



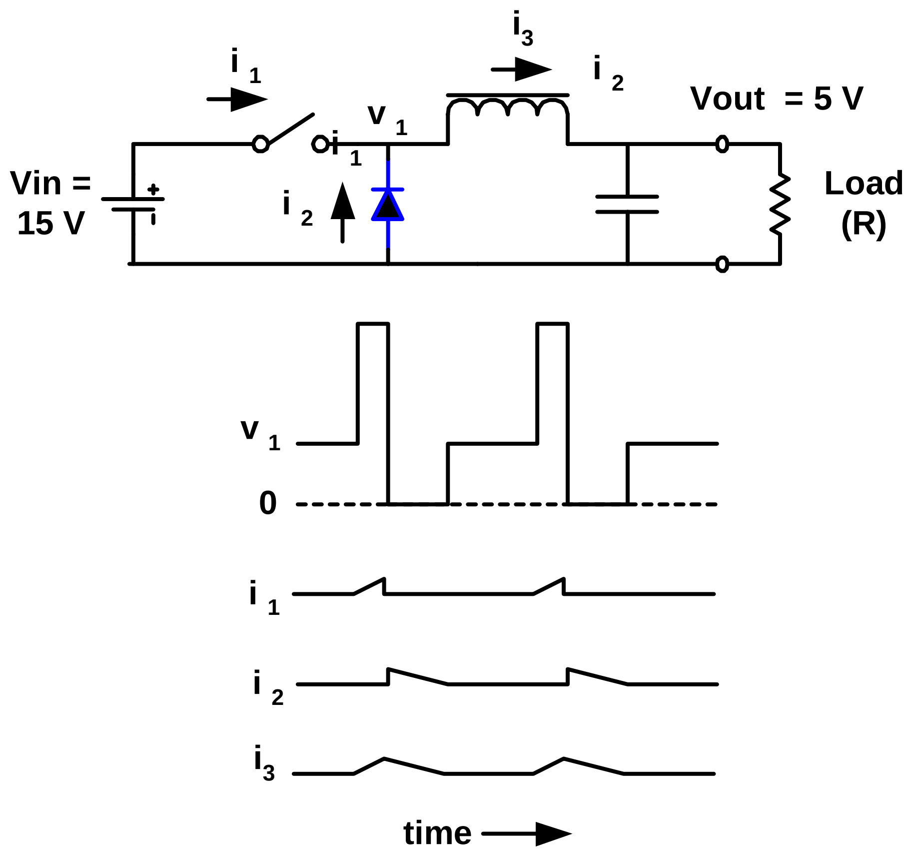
Buck Regulator
(Critical Conduction)

- Inductor current is still continuous, but just “touches” zero as the switch turns on again.
  - This is called “critical conduction.”
- Output voltage is still equal to the input voltage times D.



Buck Regulator
(Discontinuous Conduction)

- In this case, the current in the inductor is zero during part of each period.
- Output voltage is still (as always) the average of v_1.
- Output voltage is NOT the input voltage times the duty ratio (D) of the switch.
- While the load current is below the critical value, D varies with load current (while Vout remains constant).

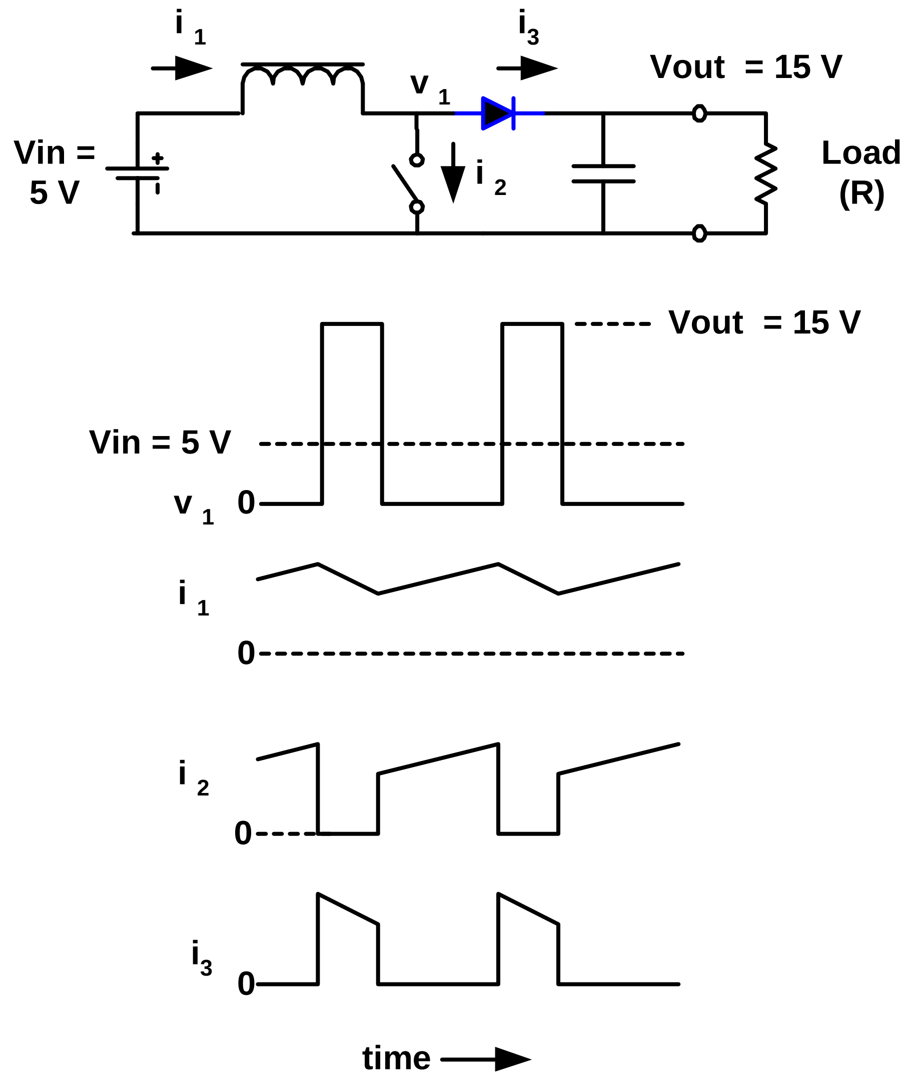


Boost Regulator

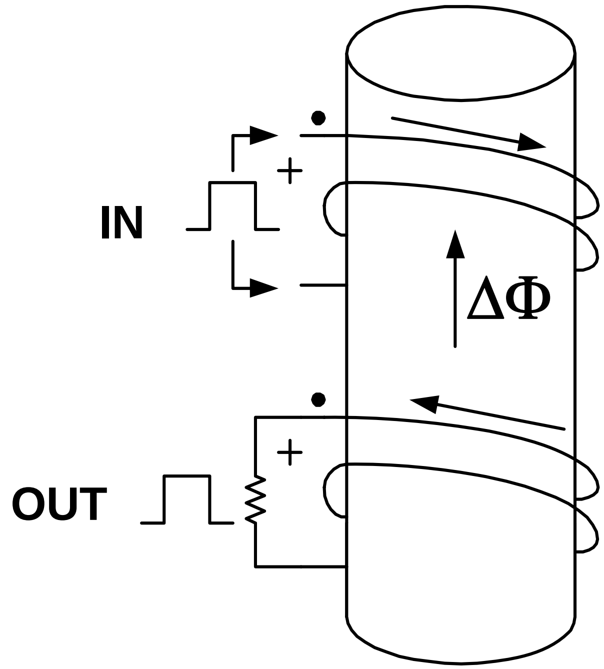
- Output voltage is always greater than (or equal to) the input voltage.
- Input current is continuous, and output current is discontinuous (the opposite of a buck regulator).
- Relationship of the output voltage to the duty ratio, D, is not as simple as in the buck regulator. In the continuous-conduction case, it is:

$$Vo = Vin\left(\frac{1}{1-D}\right)$$

- In this example, Vin = 5, Vout = 15, and D = 2/3.

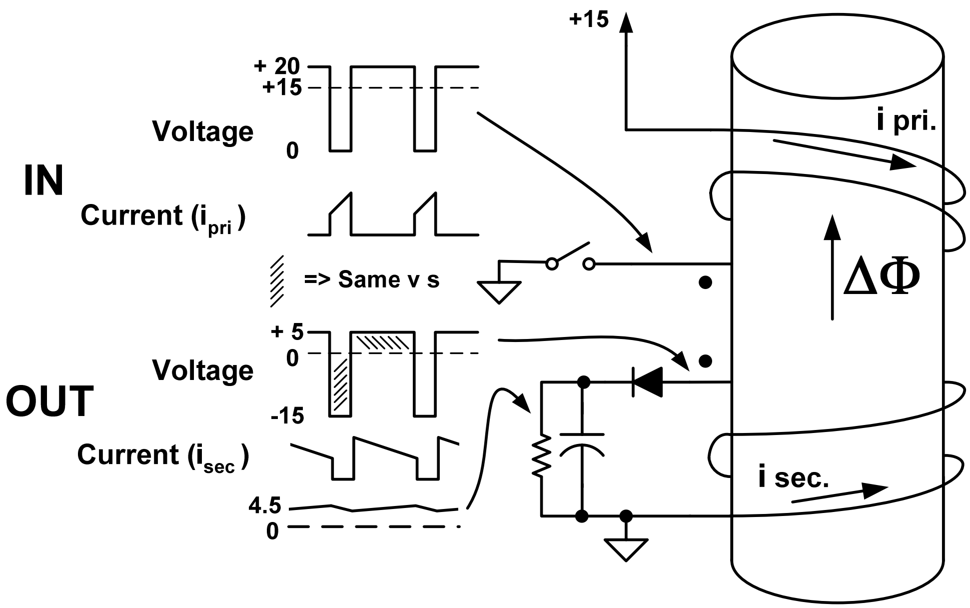


Transformer (No Energy Storage)



- Ampere-turns of all windings sum to zero.
  - Right-hand rule applies to the applied current and the resulting flux. The opposite occurs on the output winding.

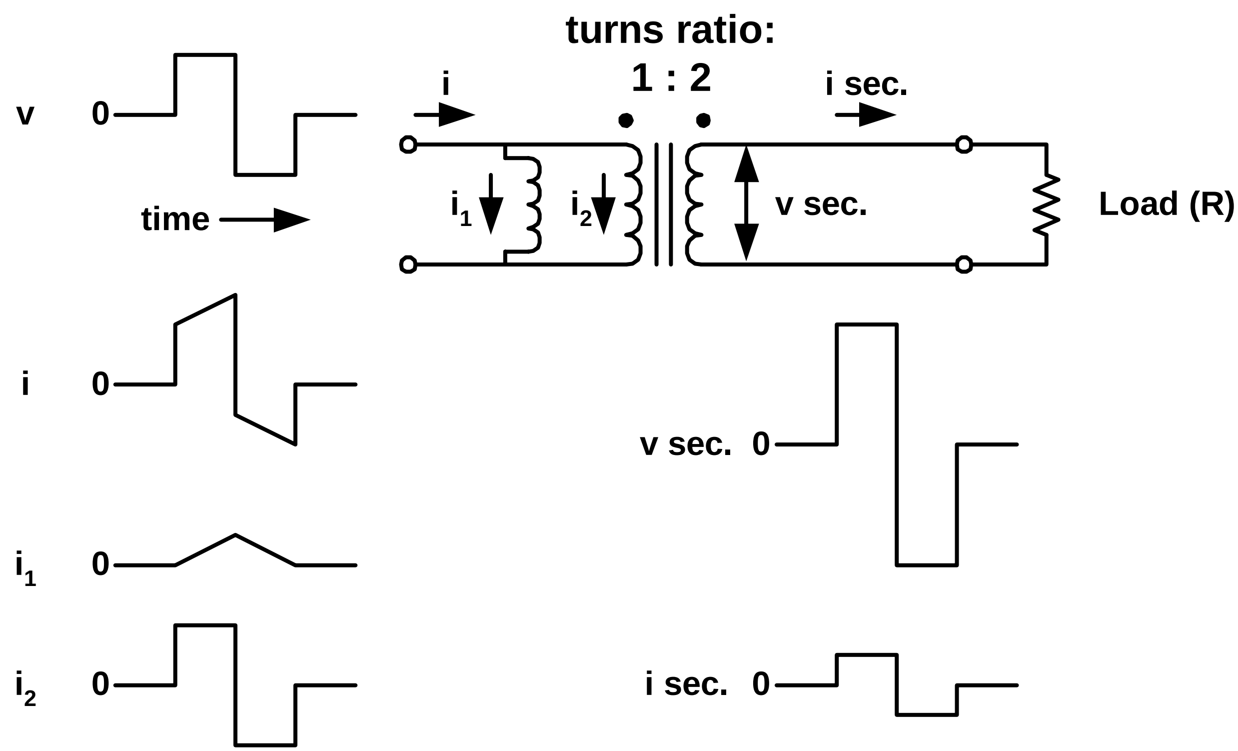
Transformer (Energy Storage)



- This is a conventional flyback transformer.
- Energy is delivered to the magnetic core during the pulse applied to the primary.
- Energy is transferred from the core to the load during the remaining portion of the cycle.
- Ampere-turns of all windings do not sum to zero over each cycle when in continuous-conduction mode. This is consistent with energy storage ($^1/_2$ L I^2).

Transformer Operation

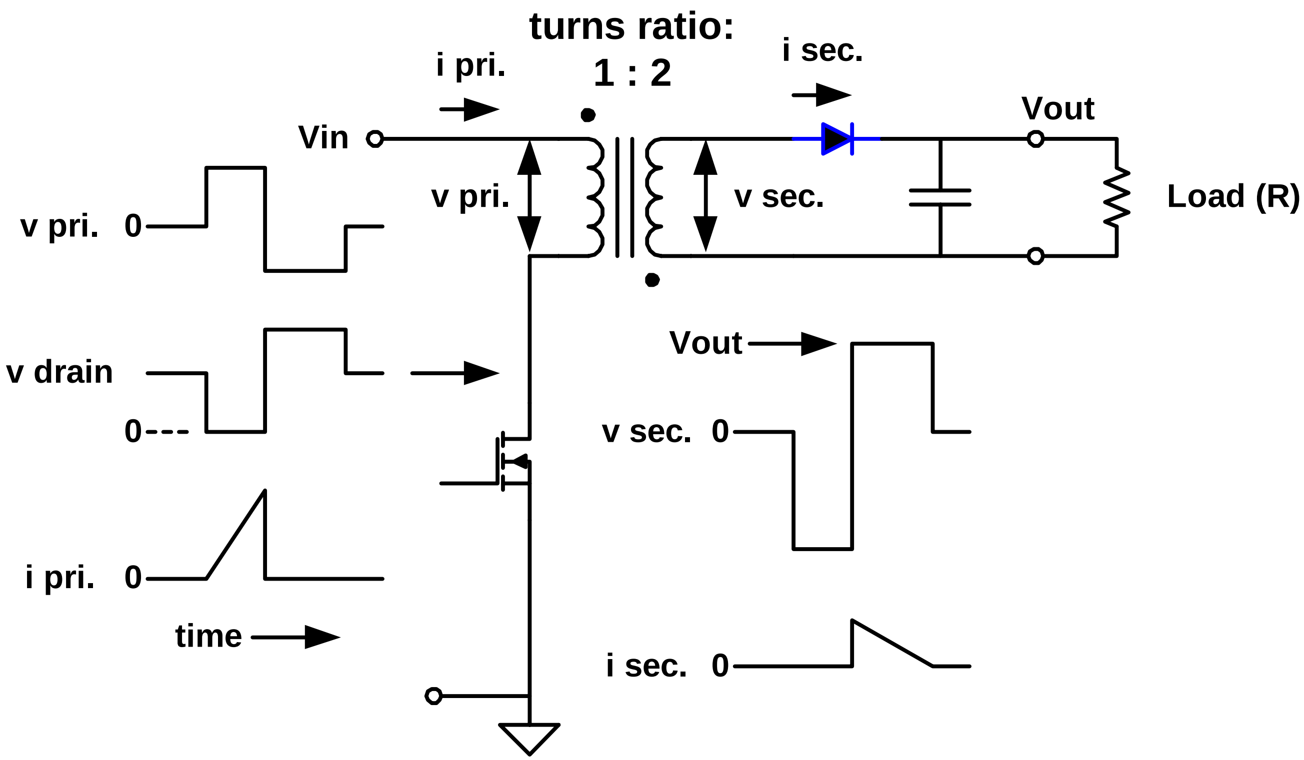
Including Effect of Primary Inductance



- This is an example of a "step-up" transformer (secondary voltage is higher than the primary voltage).
- Transformer is shown as an ideal transformer, with its primary (magnetizing) inductance as an inductor in parallel with the primary.

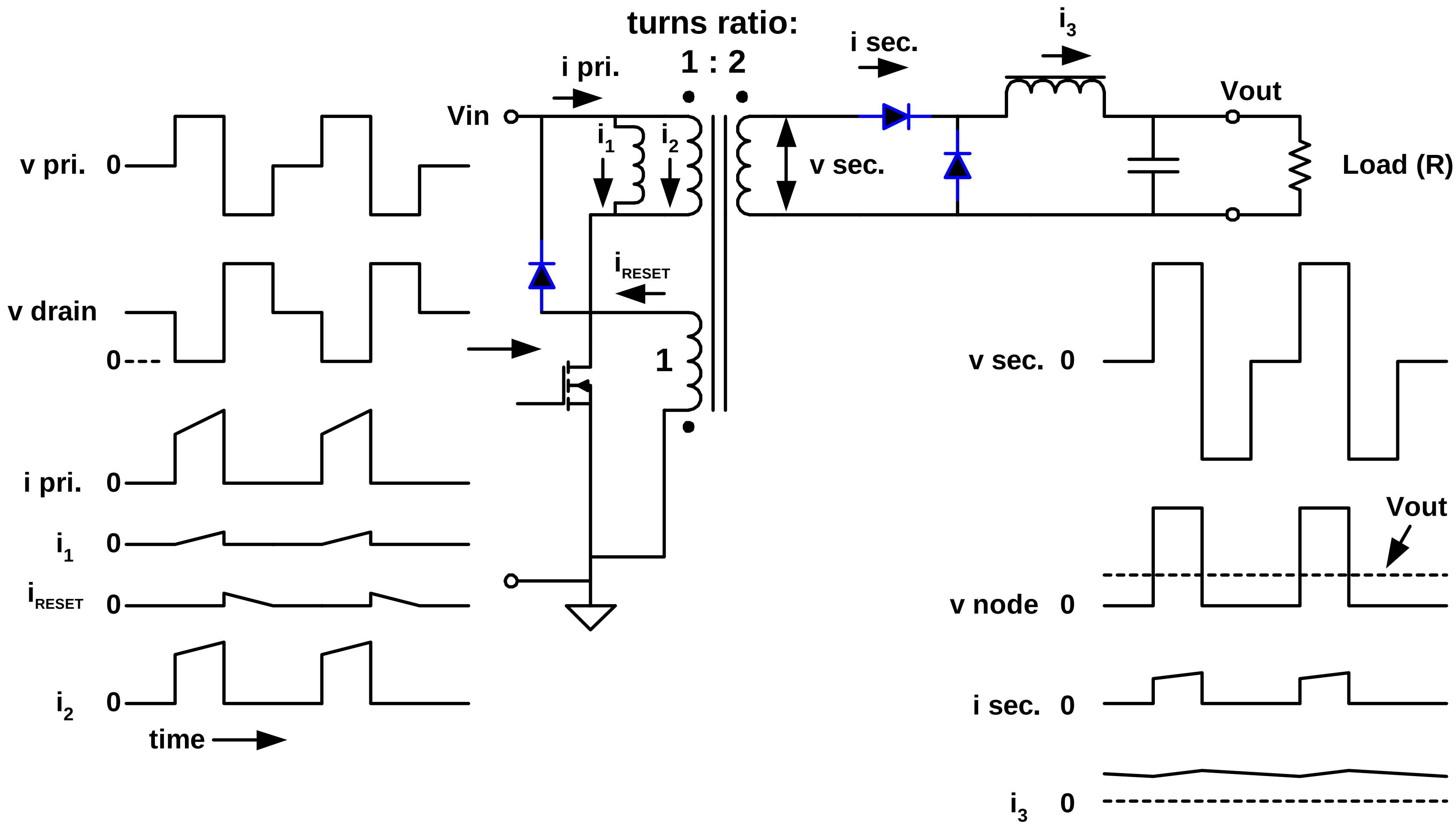
Flybaсk Transformer

Really a Multi-Winding Inductor



- Here, the primary inductance is intentionally low, to determine the peak current and hence the stored energy. When the primary switch is turned off, the energy is delivered to the secondary.
- Discontinuous conduction mode is shown in this example.

Forward Converter Transformer



- Primary inductance is high, as there is no need for energy storage.
- Magnetizing current (i_1) flows in the “magnetizing inductance” and causes core reset (voltage reversal) after primary switch turns off.

Power Factor Correction

- Power Factor (PF) is a term describing the input characteristic of an electrical appliance that is powered by alternating current (ac).
- It is the ratio of “real power” to “apparent power” or:

$$PF = \frac{P_{\text{real}}}{P_{\text{apparent}}} = \frac{(v \cdot i)_{\text{averaged over one cycle}}}{V_{\text{rms}} \cdot I_{\text{rms}}}$$

- Where *v* and *i* are instantaneous values of voltage and current, and rms indicates the root-mean-squared value of the voltage or current. The apparent power (Vrms x Irms), in effect, limits the available output power.
- The **boost regulator** is the most popular topology chosen to shape the input current to match the input voltage (usually a sine wave).

Boost Regulator

- Output voltage is always greater than (or equal to) the input voltage.
- Input current is continuous, and output current is discontinuous (the opposite of a buck regulator).
- Relationship of the output voltage to the duty ratio, D, is not as simple as in the buck regulator. In the continuous-conduction case, it is:

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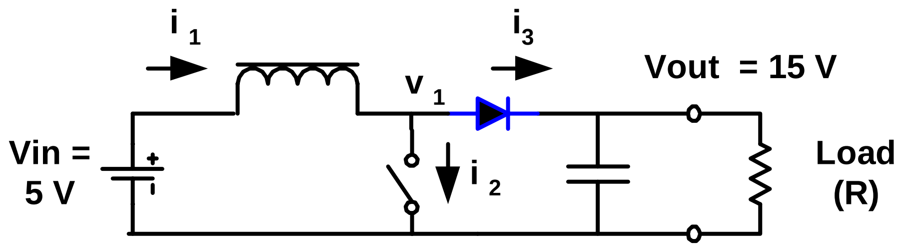
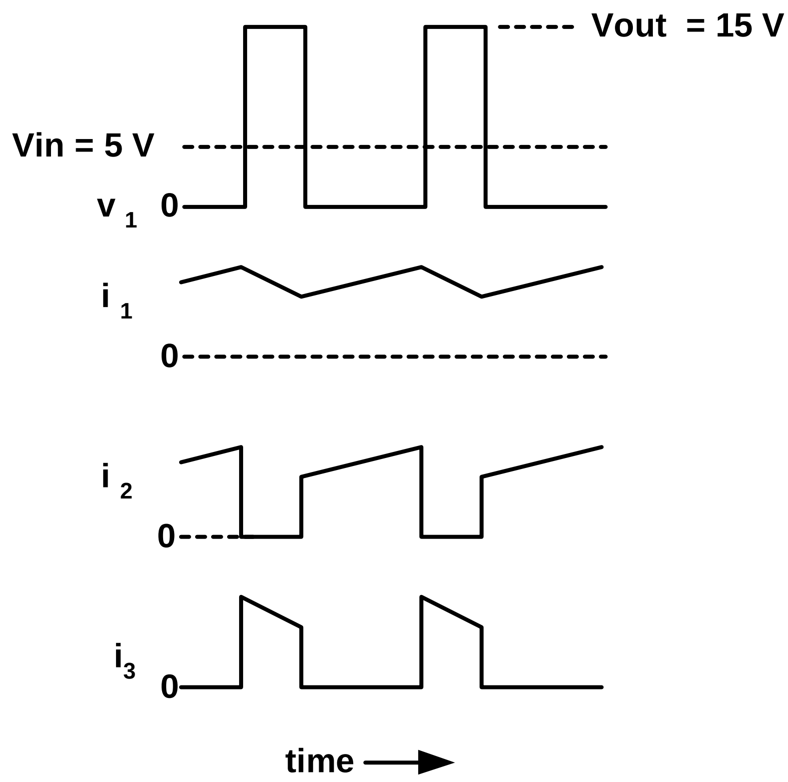




Design of the PFC Inductor

- Input: 90 – 264 Vac; Output: 400 Vdc
- Pout = 120 W (into the output converter)
- Choose: Ripple current = 0.5 A pp when input is 50% of the output voltage.
- Switching frequency f = 130 kHz.
- Inductance required:
  - Note: Use V = 200, since this represents the input at 200 V and the output at 400 V.

$$L = \frac{V \cdot t}{i_{pp}} = \frac{200 \cdot \frac{1}{2 \cdot 130{,}000}}{0.5} = 1.54\ mH$$

Winding Losses in High-Frequency Magnetics

- Power loss in switched-mode magnetic components are significant and sometimes difficult to predict.
  - Analytically, they amount to three-dimensional field problems.
  - Winding losses are usually more troublesome than core losses.
- The skin effect --- current crowding in conductors at high frequencies --- is well-known, but is not the worst part of the problem.
- Proximity effects --- due to fields induced by nearby conductors --- are much more significant, AND more difficult to predict.
- Early work, using sine waves, is inadequate to explain the losses with typical waveshapes in switched-mode power supplies.
- A knowledge of the basic principles is essential in HF magnetics design.

Eddy Currents

- Skin effect is cause by eddy currents induced in a conductor by the current in that conductor.
- Proximity effect is caused by eddy currents induced in a conductor by the current in an adjacent conductor.

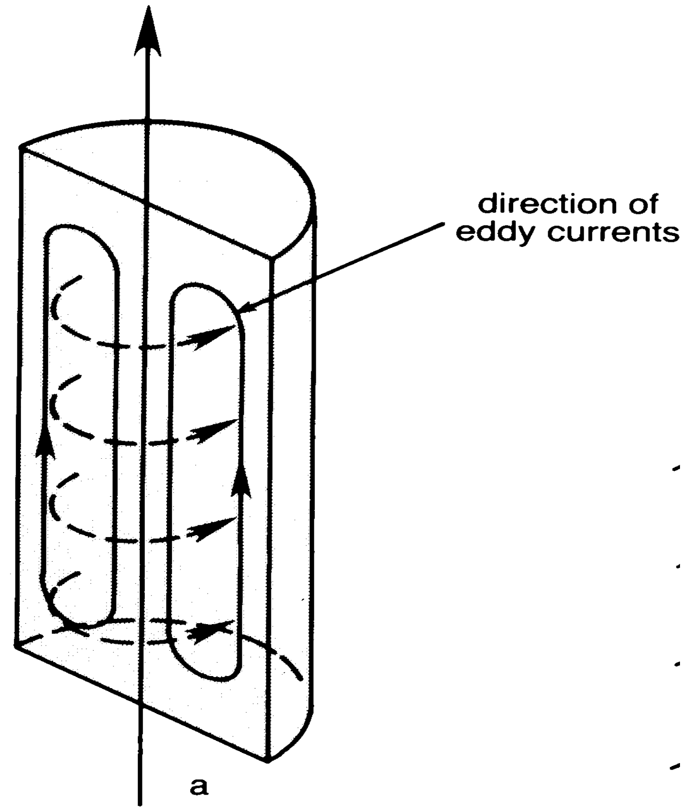
EDDY CURRENT

SKIN EFFECT

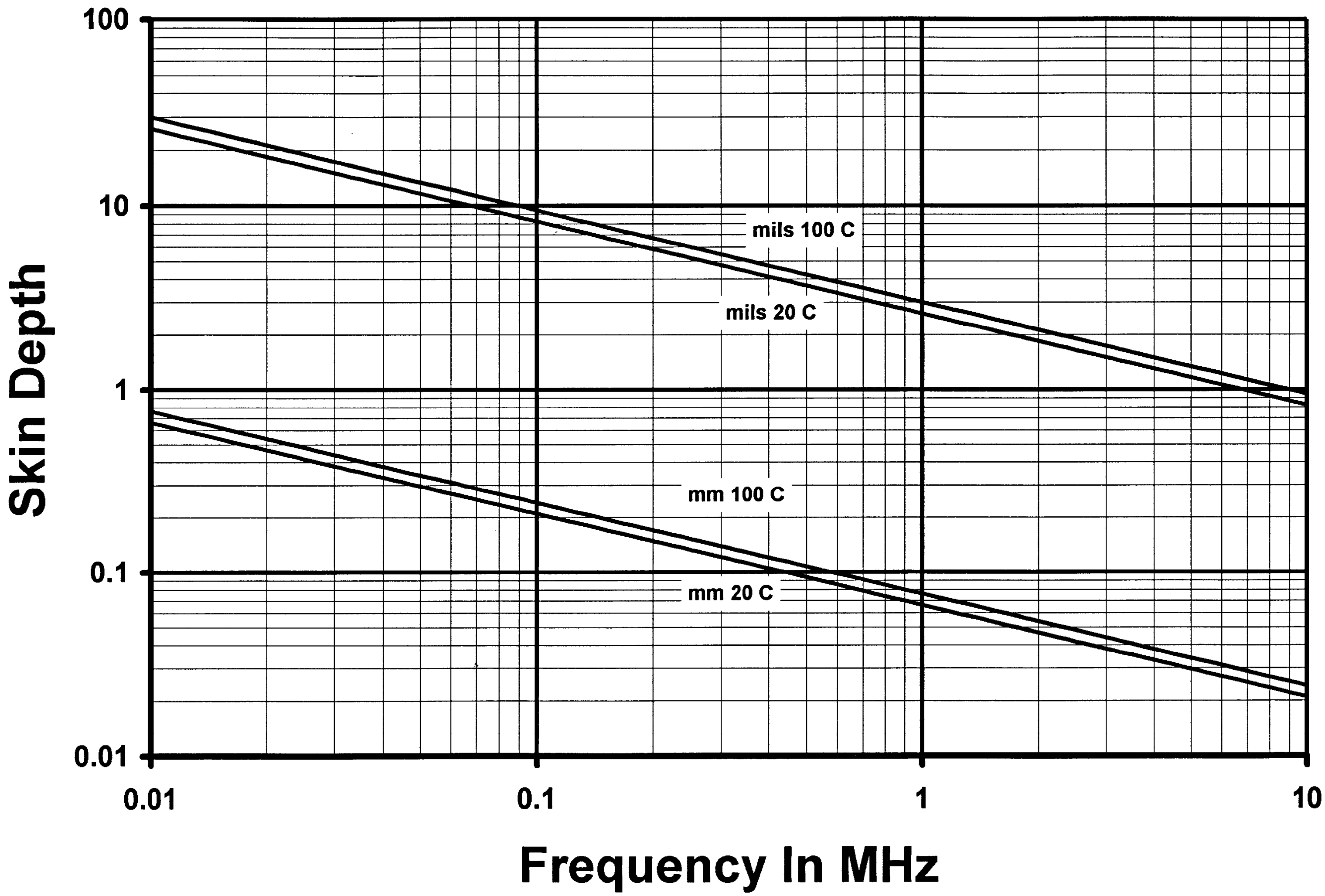
PROXIMITY EFFECT

Eddy Currents (cont'd)

- As in the earlier two-winding transformer example, magnetic field is induced by the current per the right-hand rule (dotted lines of flux).
- The flux causes eddy currents, analogous to the secondary current in the transformer.

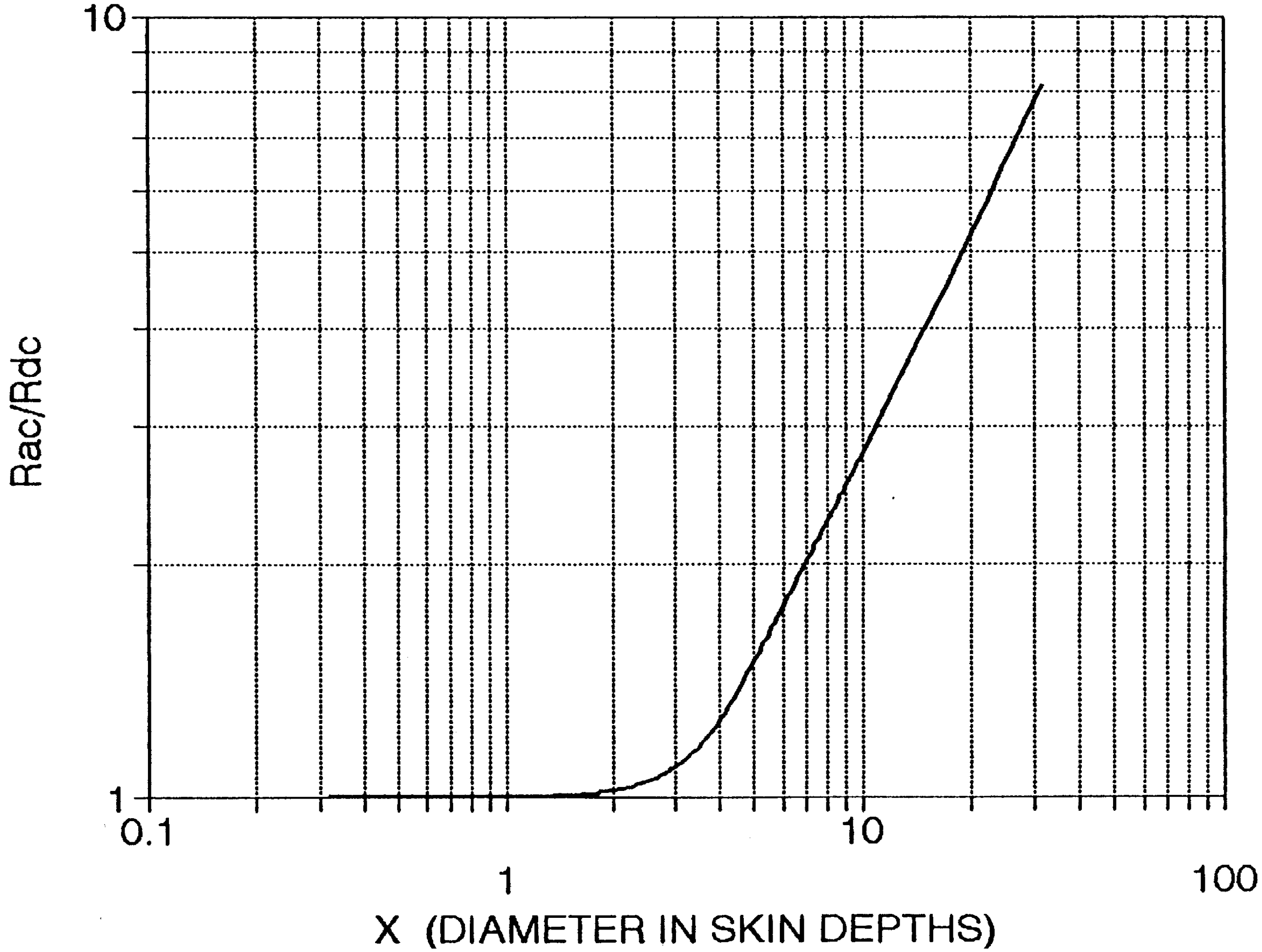


Skin Depth in Copper



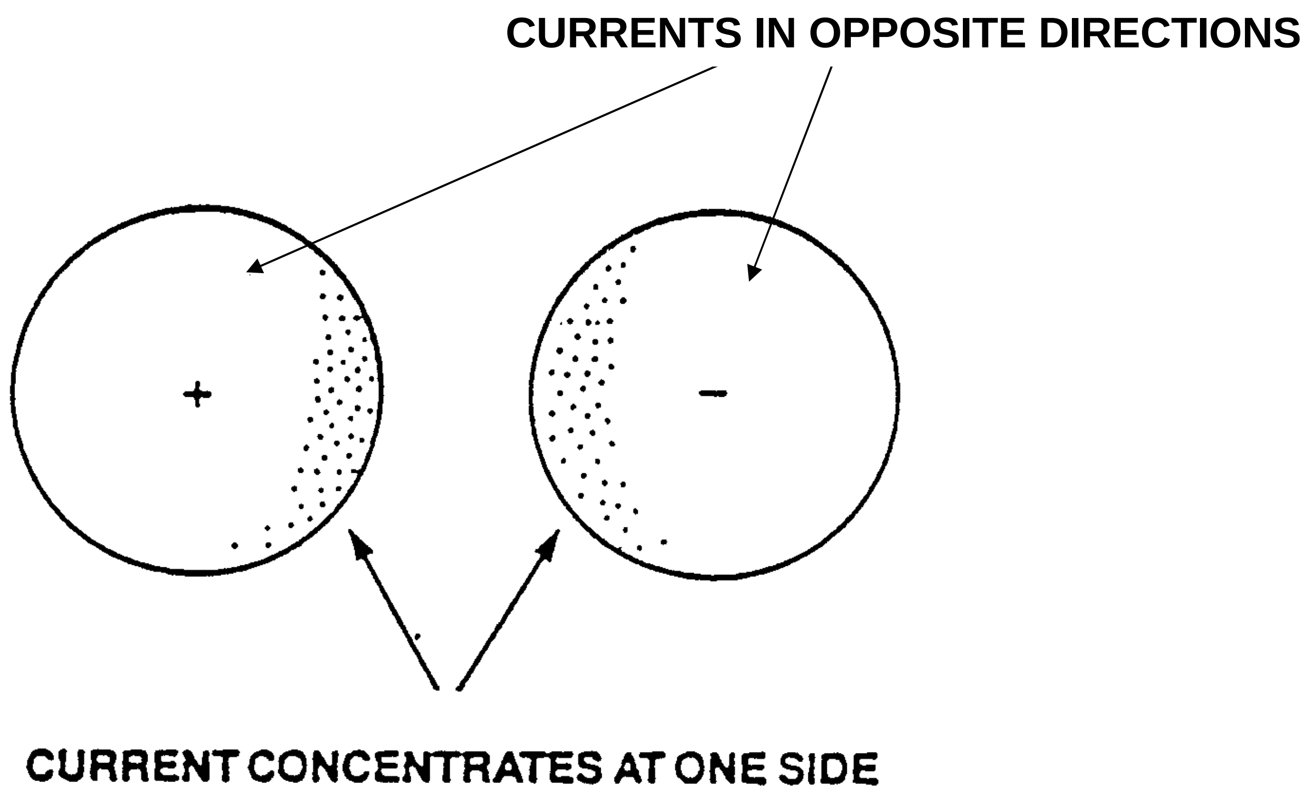
- Example: At 100 kHz, skin depth is 0.2 mm = radius of #26 wire.

Rac/Rdc vs. Diameter



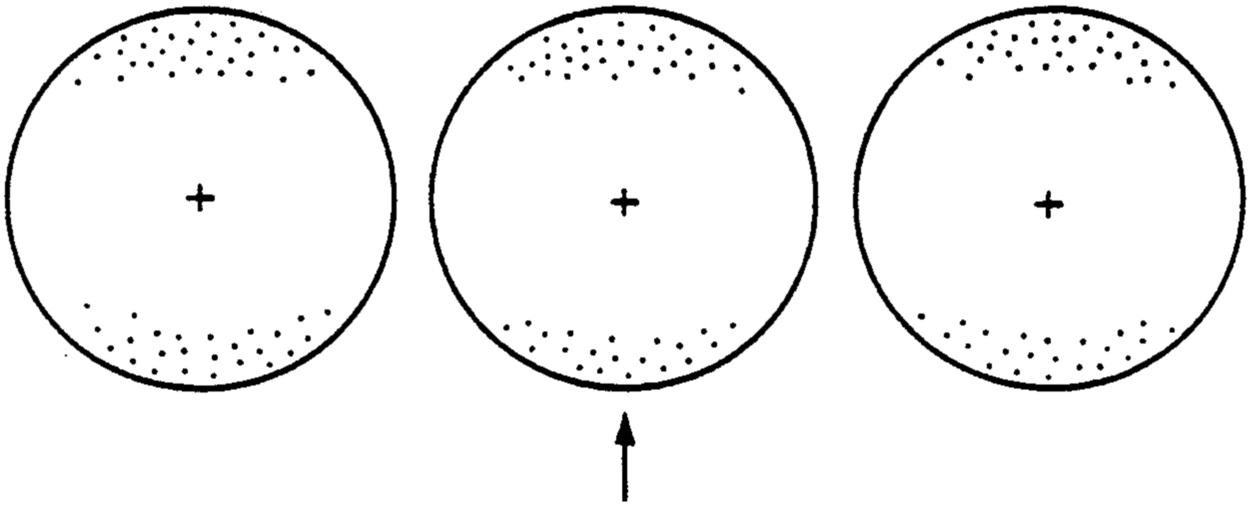
- Example: If the diameter is 7 skin depths, Rac = 2 Rdc.
  - At 100 kHz, this corresponds to # 15 wire (1.4 mm dia.).

Proximity Effect
Note Opposing Currents



- At 100 kHz, with rectangular waveforms (high harmonic content), the proximity effect is MUCH more important than skin effect.

Proximity Effect
Multiple Parallel Wires

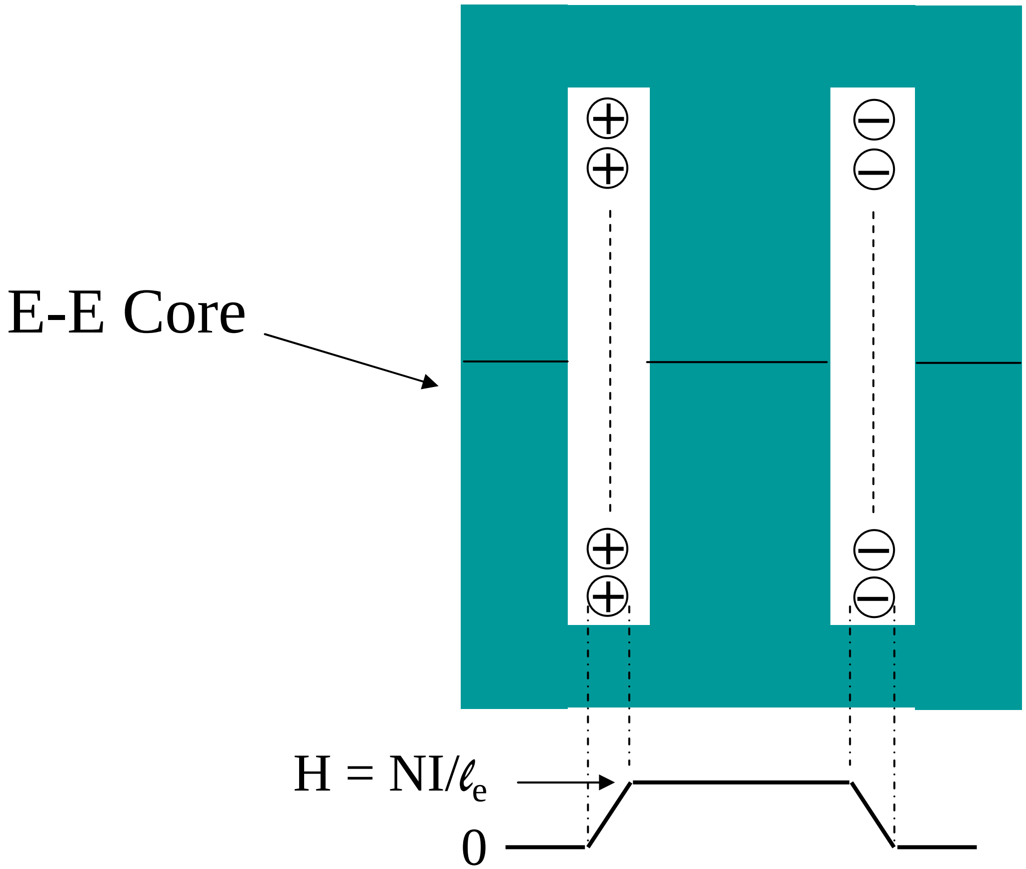


- This occurs when using copper wires in parallel in transformers and inductors.

MMF Diagrams

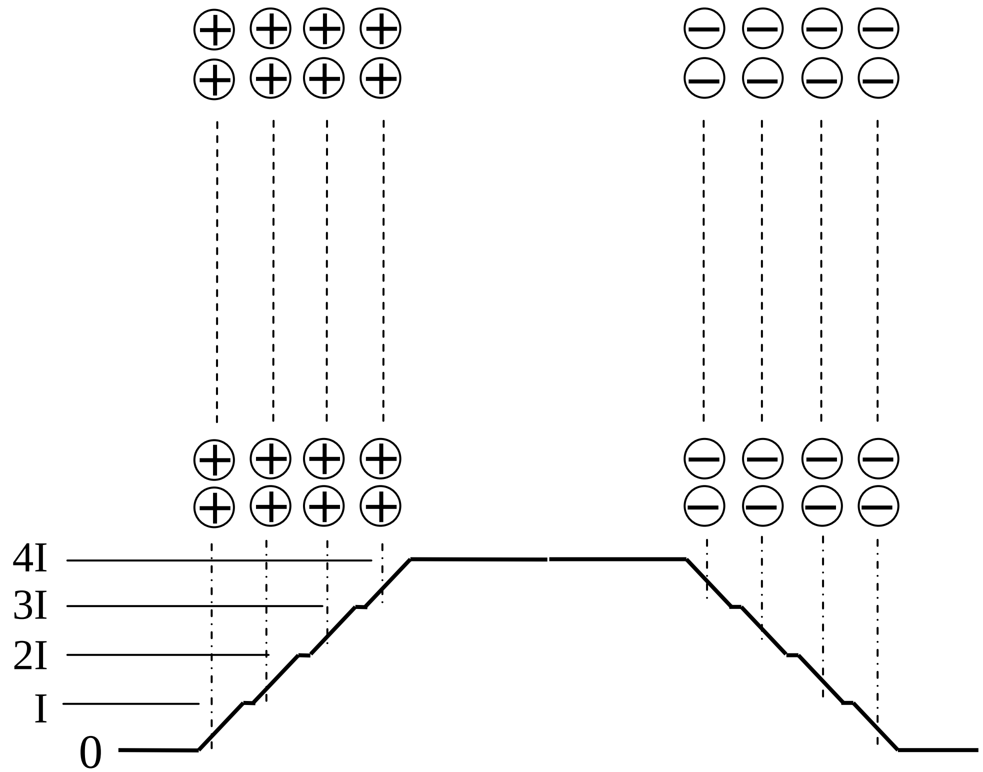
- Eddy current loss and energy stored in a field are proportional to $|H|^2$
- To design HF windings you must know what the field intensity (H) is.
- The mmf diagram is a very useful tool for determining H within a winding.
- F = NI = H le
- In the following examples we assume le = 1 so that F = H
- Even when not used for computation, the mmf diagram is powerful tool for arranging the winding structure to minimize loss and leakage inductance because it allows one to visualize the effect of different winding arrangements on the fields within a winding structure
- For simplicity, in the following examples solenoidal fields will be assumed

H Diagram for a Single-Layer Coil



- H goes from 0 at outside to NI/ℓ_e inside, then back to 0 outside.

Inductor with 4-Layer Winding



- H increases with each layer, remains at 4 I within the coil, then decreases with each layer and returns to 0 outside.
- Remember: Power loss is proportional to H^2.

Design of the Main Transformer

- Most important: Determine the range of input voltage.
- In PFC-input power supplies, the max. is usually 400 V.
- The minimum input voltage to the transformer is usually a matter of how much holdup time is required---the time that the power supply can continue to operate after an interruption of the input power.
- In ac-input power supplies, with or without PFC, there is an energy-storage capacitor at the input of the converter.
- The design of this holdup feature requires the choice of the capacitor value and the operating voltage range of the converter.
- The converter’s operating range sets the transformer design.

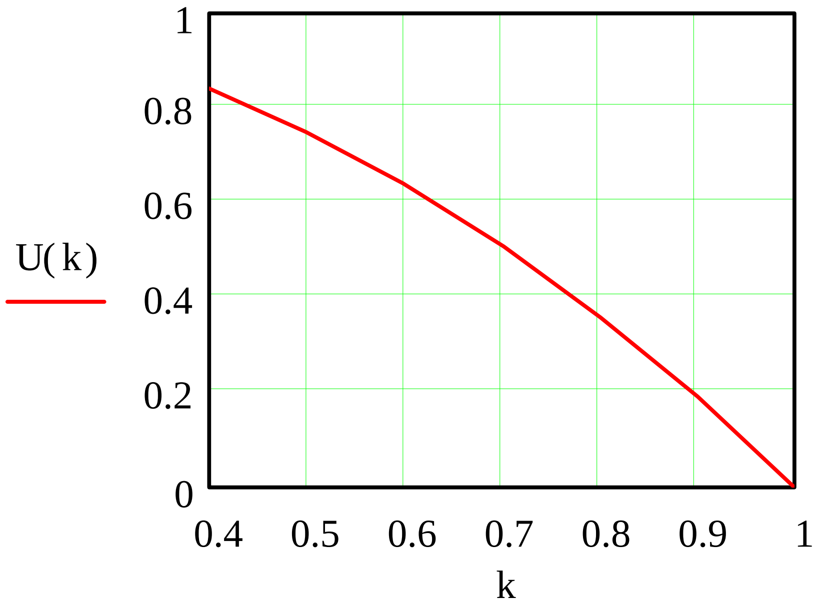
Holdup Time vs. Bus Voltage

- How much holdup time is achieved by allowing the bus voltage to decay to a given fraction of its initial value?
- Energy ***U*** extracted from the bus capacitor is

$$U = \frac{1}{2} C \cdot (V_0{}^2 - V_1{}^2)$$

$$\text{Let } V_1 = k \cdot V_0$$

$$\text{Then } U = \frac{1}{2} C \cdot V_0{}^2 \cdot (1 - k^2)$$



- Note that half of the available energy has been extracted when the voltage had decayed to 70.7% of its initial value.

Example

- Pick 400 V for the nominal bus voltage.
- Use a 450 V bus capacitor, 500 V FETs in a two-transistor forward, half-bridge or full-bridge converter, or 900 V to 1000 V FETs in a single-ended forward converter.
- Design for a final voltage of 60% (240 Vdc). Given a max. duty ratio of 45%, the nominal duty ratio will be 27%.
- This results in a minimum capacitor value of 0.4 uF per watt of output power into the output power converter, for a holdup time of 20 ms.

Details

$$k = \frac{V_{final}}{V_0}$$

$$U = P \cdot t = \frac{1}{2} C \cdot V_0^{\,2} \left(1 - k^2\right)$$

$$k = 0.6$$

$$V_0 = 400$$

$$t = .02$$

$$C = \frac{2 \cdot P \cdot t}{V_o^{\,2}(1 - k^2)}$$

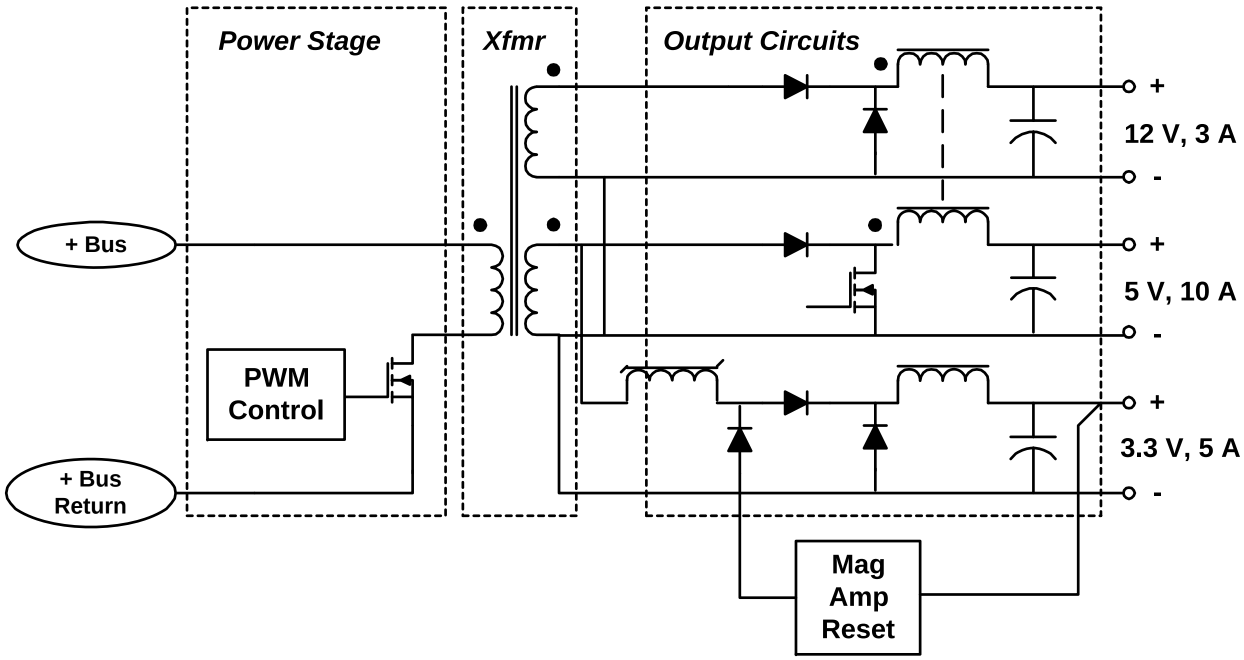
And the answer is...

$C = 0.4$ uF per watt (into the final power stage)

Main Transformer Design

- High-frequency transformers are a challenge.
  - Core losses are usually not negligible.
  - Winding losses are almost always significant.
  - Winding losses are usually much more difficult to deal with in transformers than in inductors, as the high-frequency components of winding currents are large, compared to the average values of currents.
  - The high-frequency winding losses are very dependent on the winding structure.
    - Layers, wire sizes, interleaving techniques are all important, and some of the tradeoffs are counterintuitive.

Transformer Requirements



- Per the earlier discussion, design for a final voltage of 60% (240 Vdc). Given a max. duty ratio of 45%, the nominal duty ratio will be 27% (with 400 Vdc bus).
- Duty ratio in the 3.3 V output will be approx. 3.3/5 of these.

Essential Specifications

• Vin range	240 – 400 V
• Output 1	5 V, 10 A
• Output 2	3.3 V, 5 A
• Output 3	12 V, 3 A
• Frequency	100 kHz
• Max. temp. rise	40 ºC
• Cooling	Natural convection
• Duty ratio	27% to 45%

Output Voltages and Turns Ratios

- Assume the 5 V rectifier is a Schottky, with .4 V drop
- Assume the 12 V rectifier has a .8 V drop
- These are perhaps generous, but include IR drops in wdgs.
- Output voltages are then 5.4 V and 12.8 V
  - We're losing a diode drop both during the pulse and during the rest of the cycle, so simply add the diode drop to the output voltage.
- Turns ratio between output windings:
- 12.8/5.4 = 2.37. Use 2 t and 5 t ? 12 V output will be 5/2 x 5.4 – 0.8 = 12.7 V. If 3 t and 7 t, it will be 11.8 V. Go for the 2 t and 5 t , if these result in a reasonable flux density.

$$N_p = N_{s1} \cdot \frac{V_p}{V_{s1}} = 2 \cdot \frac{400}{20} = 40 \text{ turns.}$$

- Peak voltage on the 5 V secondary is 5.4 V / (d = .27) = 20 V.

Core Selection

- Select size by manufacturer's recommendation, based on power and frequency, or by area product.

$$AP = A_w A_e = \left(\frac{P_O}{K \cdot \Delta B \cdot f} \right)^{\frac{4}{3}} \ \mathrm{cm}^4$$

- Where K = 0.014 for forward converters
- Choose ΔB for a core loss of 100 mW/cm^3 (ΔB is twice the B shown on the core loss curves).
- The above formula is based on a current density (J) of 420 A/cm^2 and a window utilization of 40% copper.
- For Magnetics P material, B = 0.12 T ΔB = 0.24 T
- For 120 W, 100 kHz: AP = 0.253 cm^4 T
- Choose a PQ 2620 core (approx. 26 mm sq. footprint; 20 mm high).

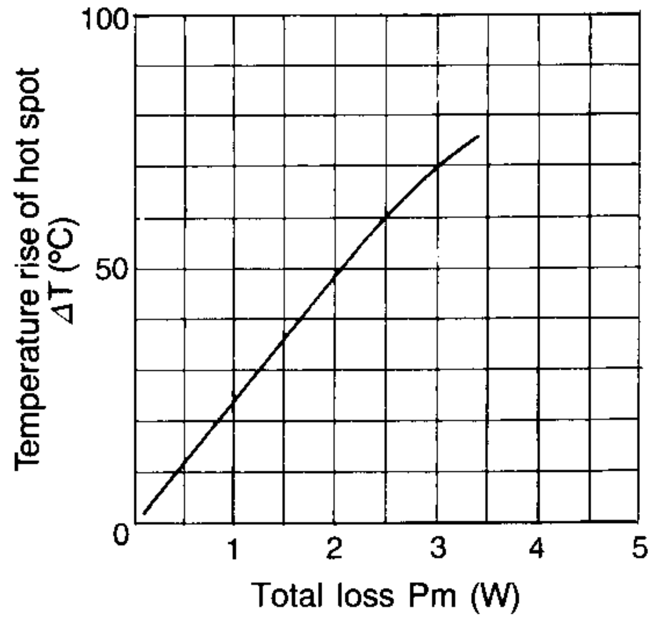
A Handy Table

Sorted by WaAe (Area Product)														
Core		Ae	Wa	WaAe	Ve	Bobbin	Overall (mm)			Floor	Winding (mm)		Notes	
Type	Mfr.	cm^2	cm^2	cm^4	cm^3	Mfr.	L	W	H	Area, cm^2	Width	Height		
PQ2020	TDK	0.62	0.36	0.22	2.8	TDK	23	23	18	5.3	10.7	3.4		Without clamp
EFD25	Thomson	0.58	0.4	0.23	3.3	B&B	26	25	13	6.5	16.7	2.4		Horiz. mount
ETD24	TDK	0.56	0.45	0.25	3.5	TDK	34	29	22	9.7	17.2	2.6		Horiz. mount
LP22/13	TDK	0.68	0.46	0.31	3.3	TDK	32	26	19	8.4	13.4	3.4		Horiz. mount
PQ2620	**TDK**	**1.19**	**0.31**	**0.37**	**5.5**	**TDK**	**29**	**27**	**22**	**7.8**	**9.2**	**3.4**		**Without clamp**
EFD30	Thomson	0.69	0.54	0.37	4.3	B&B	31	30	13	9.3	20.4	2.6		Horiz. mount
RM10	Siemens	0.98	0.42	0.41	4.3	Siemens	39	25	23	9.7	10.3	4.1		Power bobbin
RM10	Siemens	0.98	0.42	0.41	4.3	Siemens	25	25	19	6.1	10.5	4.0		Regular bobbin
LP32/13	TDK	0.7	0.72	0.50	4.5	TDK	41	26	19	10.5	21.1	3.4	1	Horiz. mount

- List the standard cores your company uses, with the parameters you'll use in your designs. With this in an Excel spreadsheet, you can sort by AP, floor area, height, as needed.

Determine the Core's Thermal Resistance

Temperature rise vs. Total loss for PQ26/20 core (Typical) (Ambient temperature: 25°C)



- PQ2620 core has thermal resistance of 24 ^{o}C/W (computed by calculating the slope, 60 ^{o}C / 2.5 W = 24 ^{o}C/W).

Determine Allowable Power Loss & B

- $P_{lim} = {}^{o}C_{rise}/R_T = 40 / 24 = 1.63$ watts
- Apportioning half to core loss, half to wire loss:
  - Pcore = 0.8 W max.
  - Pwire = 0.8 W max.
- Core volume is 5.5 cm^3
- Therefore, core material loss is 0.8 W / 5.5 cm^3, or 145 mW/cm^3.
- This corresponds to a flux density of 0.12 T in Magnetics P material.

Calculate the Number of Turns

- Flux density is determined by volt-seconds per turn, so it can be calculated from any winding. Using the primary,

$$\text{Since } V = N\frac{d\Phi}{dt}, \text{ we can write } N_P = \frac{V_P \cdot t}{\Delta B \cdot A_e} = \frac{V_P \cdot \frac{d}{f}}{2B \cdot A_e}$$

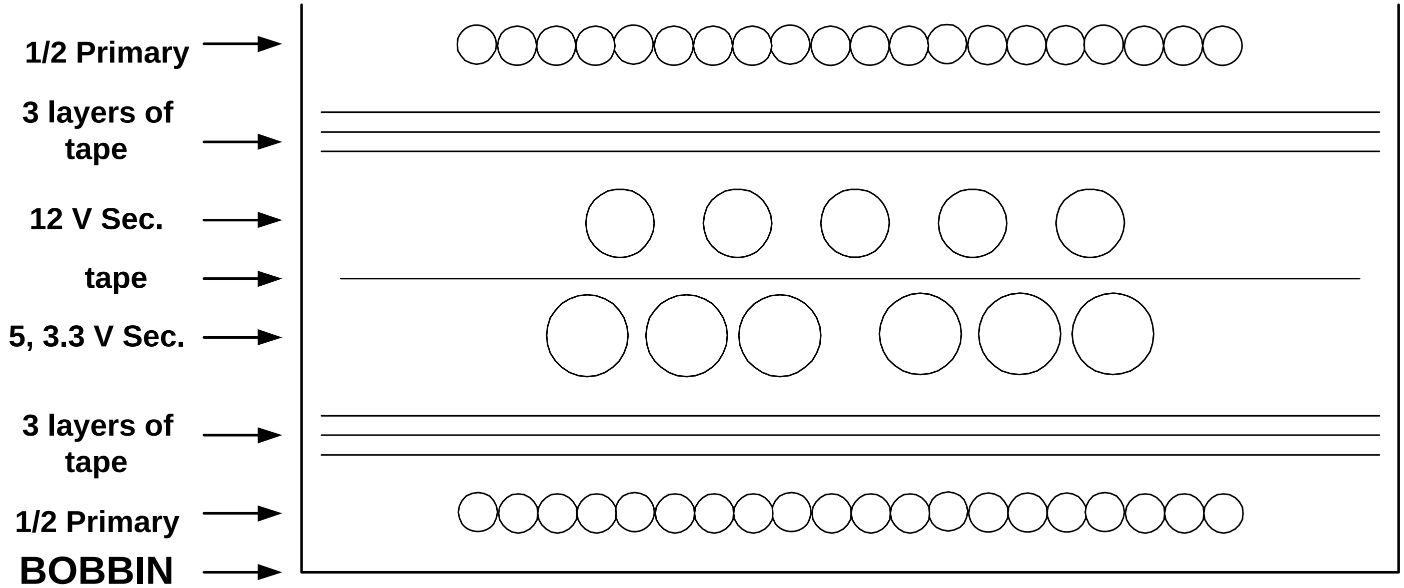
$$N_P = \frac{400 \cdot \frac{0.27}{100{,}000}}{2 \cdot 0.12 \cdot 1.19 \cdot 10^{-4}} = 37.8 \text{ turns}$$

- This corresponds to the desired core loss of 0.8 W. Raising or lowering it will simply move the core loss down or up (respectively). Loss is proportional to $B^{2.86}$ at 100 kHz in “P” material. 5% less turns will cause 15% more loss.
- Our previous calculation resulted in 40 turns on the primary, which will simply result in less core loss.

Designing the Winding Structure

- This is perhaps the most interesting and creative part of transformer design.
- Adjust the secondary turns to match the desired output voltages (5 V and 12 V)
- Adjust the primary turns to optimize the layer structure.
- In both cases, adjust conductor sizes and shapes to minimize fractional layers and take advantage of the available space.
- A popular way to minimize winding losses is to split the primary winding, winding half of the turns, then the secondary turns, and finally, the other half of the primary turns.

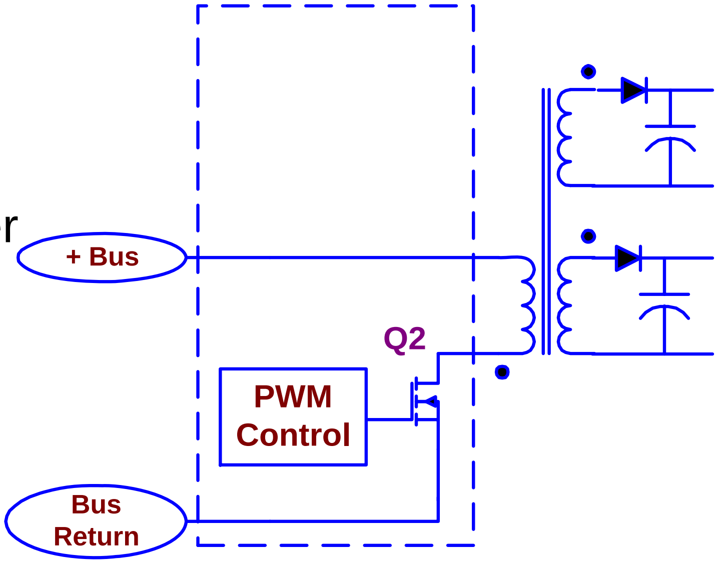
Winding Structure



- Analysis of build height:
  - Primary layers: 2 x 0.374 mm
  - 5 V sec: 0.887 mm
  - 12 V sec: 0.714 mm
  - 7 layers tape @ .127 mm.
- Grand total: 3.283 mm. Bobbin height is 3.4 mm, so we're IN.

Flyback

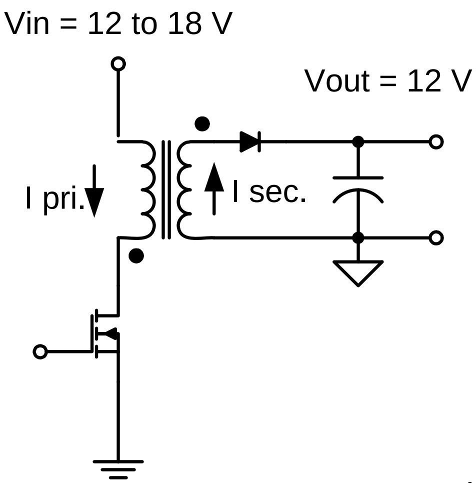
- Transformer stores energy
  - Designed like an inductor
  - Causes it to be larger
  - Really an "integrated magnetic," because it combines the transformer and inductor functions in one core

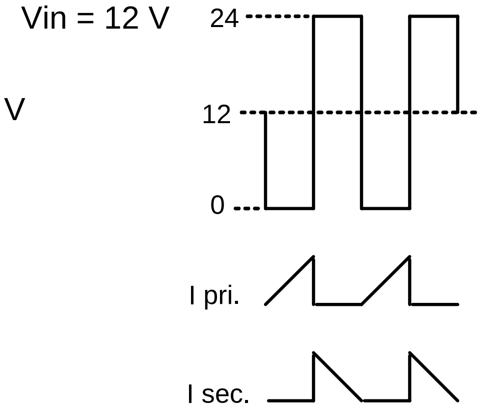


Flyback

- For discontinuous mode, design the transformer so that the duty ratio (D) just approaches maximum at max. load and min. input voltage.
  - In this example, max. D is 0.5, and min. Vin is 12 V.
- As Vin rises to 18 V, the slope of the input current rises by di/dt = V / L.
  - Ipri. rises to the necessary peak value in less time, so primary pulse is narrower, as shown in this example.
  - Volt-seconds on any winding must average to zero, so with 18 V in, the pulse width decreases by 12/18.
  - Load is constant, so secondary pulse width is same as before.
  - Peak current simply transfers from primary to secondary when the switch turns off. In this example, turns ratio is 1:1.
- Transformer size is determined by the power and frequency.

Design can be modified for different secondary voltage(s) by changing secondary turns and wire size, and primary operating conditions stay the same.



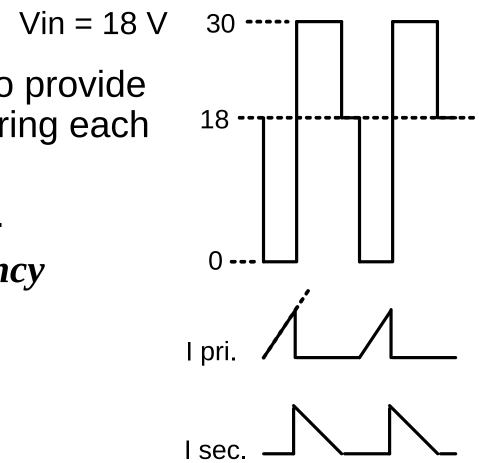


- Inductance is chosen to provide the required energy during each pulse.
- Energy = power x time.

$$U = Pin \bullet t = Po \bullet t / efficiency$$

$$Li^2 = Vin \bullet Iin \bullet t$$

$$L = \frac{Vin \bullet Iin}{f}$$



For More Information

- View the extensive portfolio of power management products from ON Semiconductor at www.onsemi.com
- View reference designs, design notes, and other material supporting the design of highly efficient power supplies at www.onsemi.com/powersupplies