Switched Mode Power Conversion

Transformers

Devices for Efficient Power Conversion

Switches

Inductors

Transformers

Capacitors

Switched Mode Power Conversion

Transformers

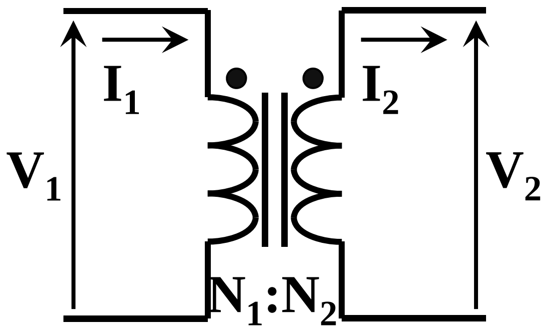
Transformers Match Voltage Levels.
Ideally They Do Not Store Energy.

In Power Converters, Transformers Provide Electrical Isolation as Well.

Switched Mode Power Conversion

Transformers

Transformers Match Voltage Levels.

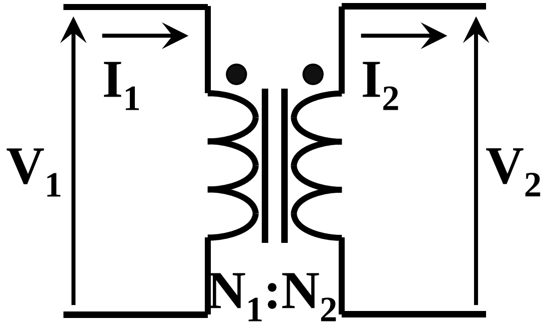


$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Switched Mode Power Conversion

Transformers

Transformers Provide Electrical Isolation

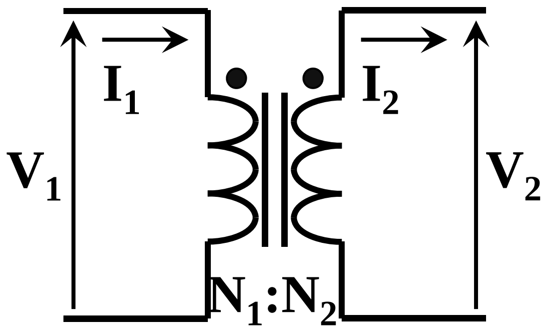


$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Switched Mode Power Conversion

Transformers

Efficiency of Power Conversion is Unity



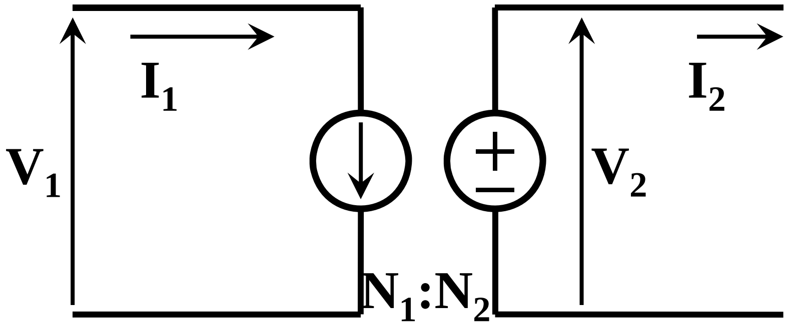
$$V_1 I_1 = V_2 I_2$$

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

Switched Mode Power Conversion

Transformers

Circuit Schematic



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

$$I_1 = \frac{N_2}{N_1} I_2$$

Switched Mode Power Conversion

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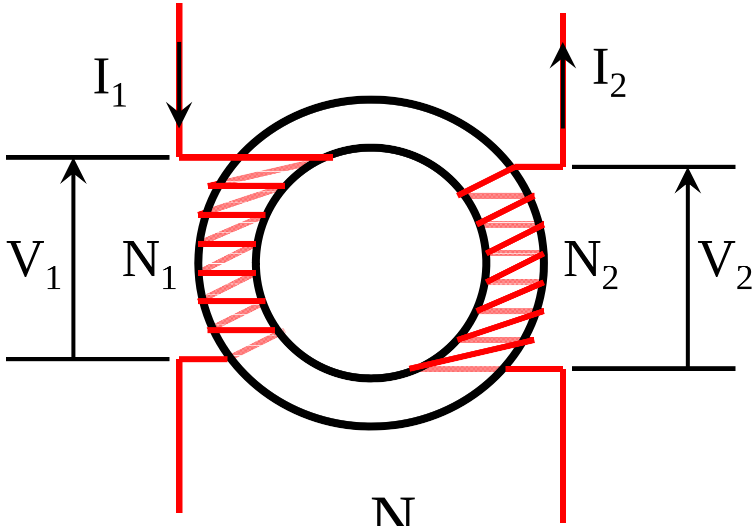
Magnetic Circuit



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

$$I_1 = \frac{N_2}{N_1} I_2$$

Switched Mode Power Conversion

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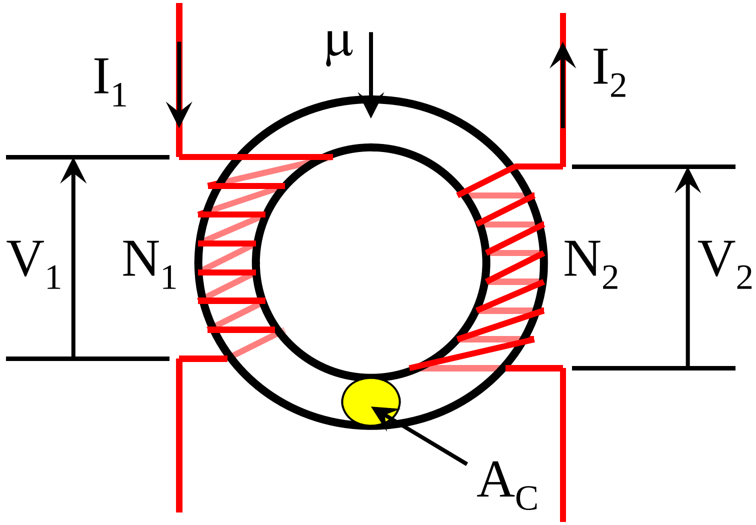
Magnetic Circuit



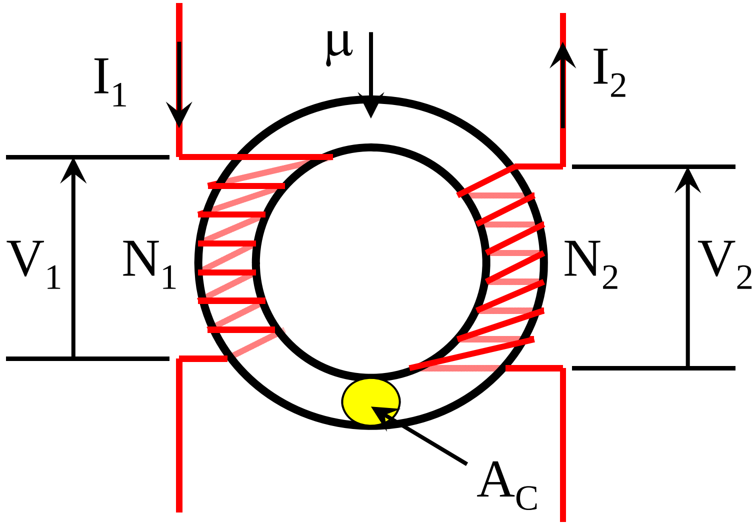
Transformer Does Not Store Energy

The Core Reluctance is Ideally Zero

Switched Mode Power Conversion

Transformers

Magnetic Circuit



Core Shape is Chosen for Convenience

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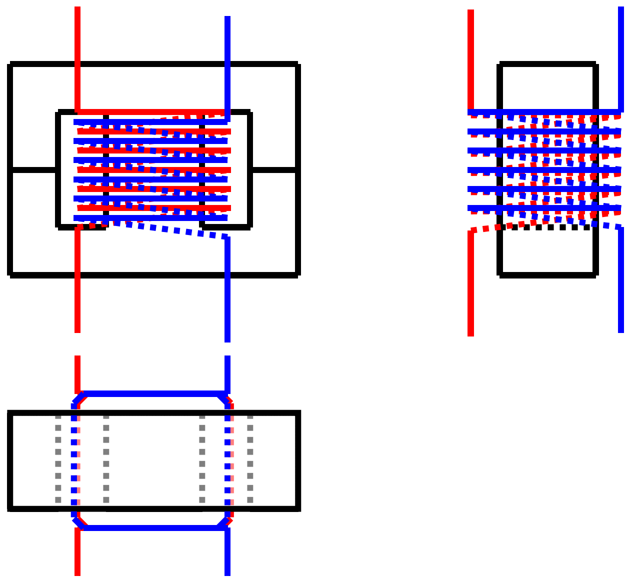
Magnetic Circuit

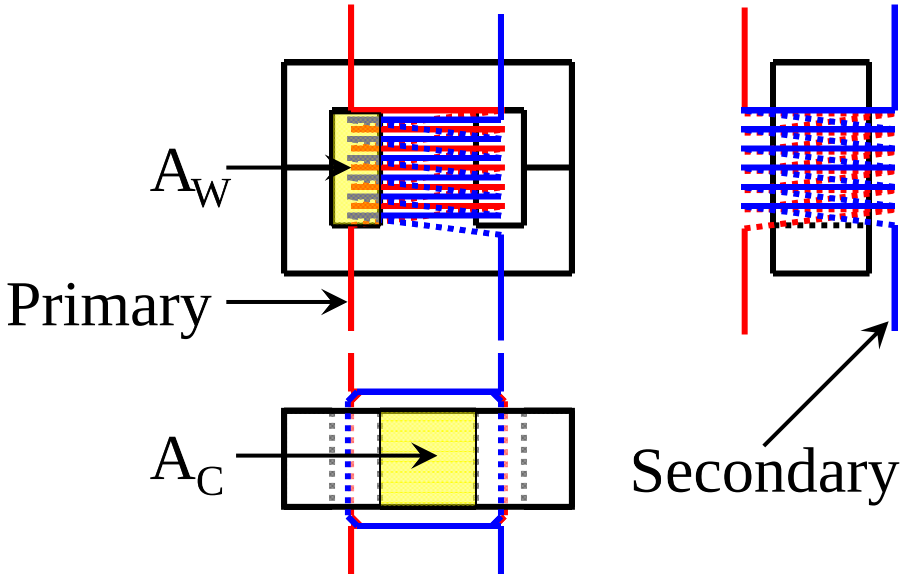


EE Cores

Switched Mode Power Conversion

Transformers

Magnetic Circuit



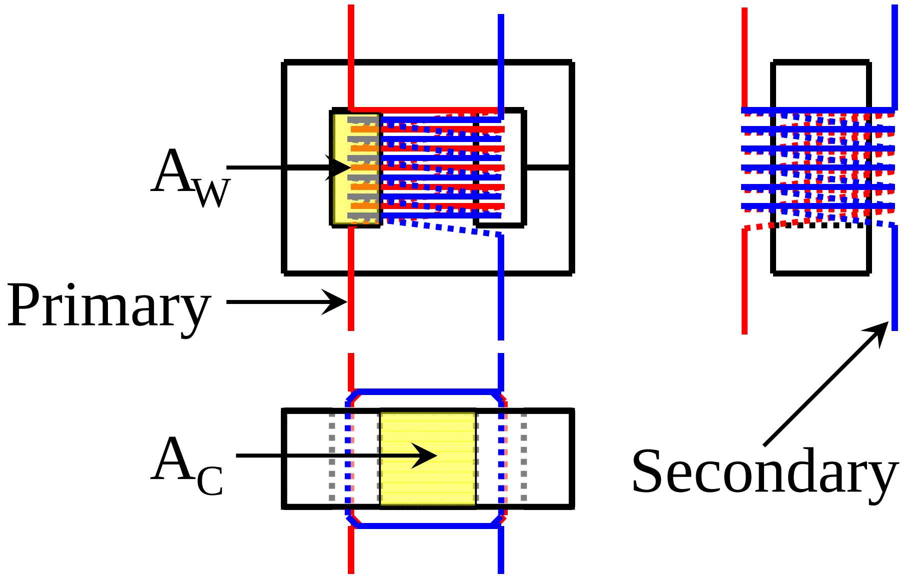
Window Accommodates Both Primary & Secondary

Core Links Both Primary & Secondary

Switched Mode Power Conversion

Transformers

Voltage Equation



$$V_1 = N_1 \frac{d\Phi}{dt}; V_2 = N_2 \frac{d\Phi}{dt}$$

Switched Mode Power Conversion

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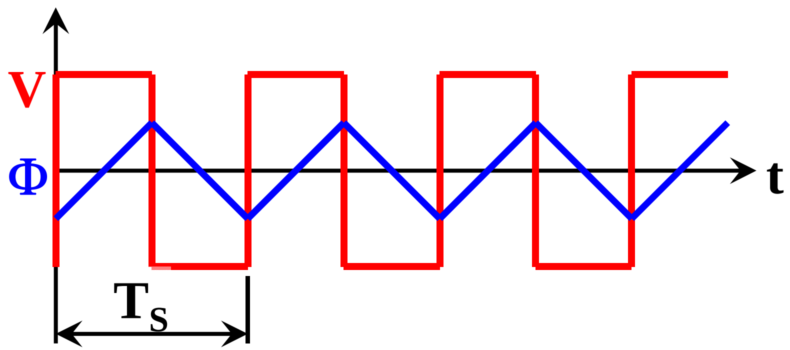
Flux Waveform – Square Wave Primary Voltage



$$V = N\frac{d\Phi}{dt}$$

Flux Swings Symmetrically Between $-\Phi_m$ and $+\Phi_m$

Switched Mode Power Conversion

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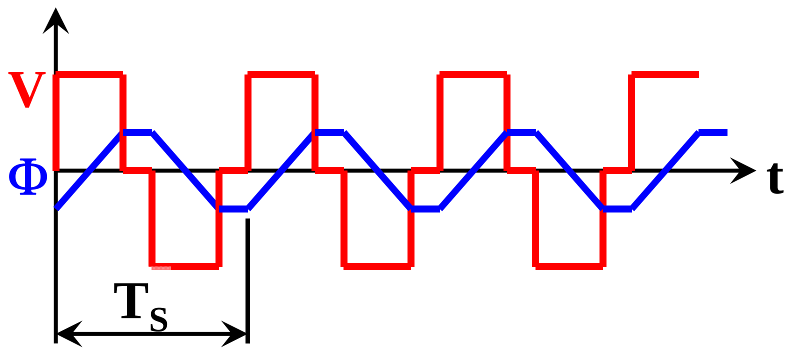
Quasi-Square Wave Primary Voltage



$$V = N\frac{d\Phi}{dt}$$

Flux Swings Symmetrically Between $-\Phi_m$ and $+\Phi_m$

Notice the Dwell Time in Flux

Switched Mode Power Conversion

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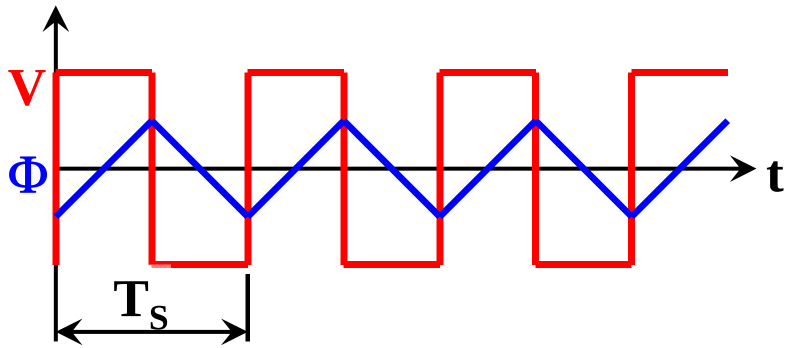
Voltage – Core Area Equation



$$V = N\frac{2\Phi_m}{T_S/2} = N*4*B_m*A_C*f_S$$

$$V_1 = N_1*4*B_m*A_C*f_S; V_2 = N_2*4*B_m*A_C*f_S$$

Flux Swings Symmetrically Between –Φ_m and +Φ_m

Switched Mode Power Conversion

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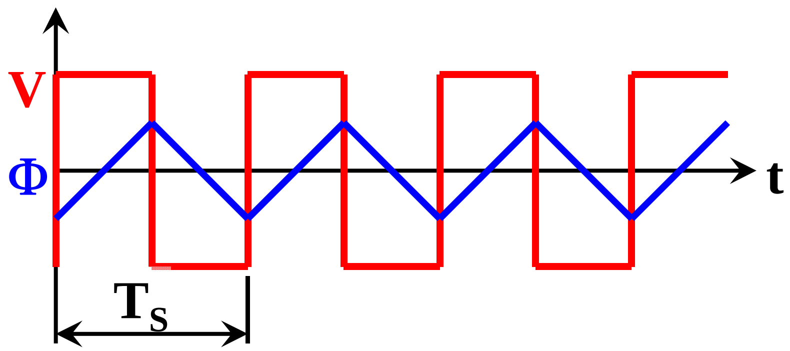
Voltage – Core Area Equation



$$V_1 = 4N_1B_mA_Cf_S$$

$$V_2 = 4N_2B_mA_Cf_S$$

A_C is a Function of Voltage and Frequency

Switched Mode Power Conversion

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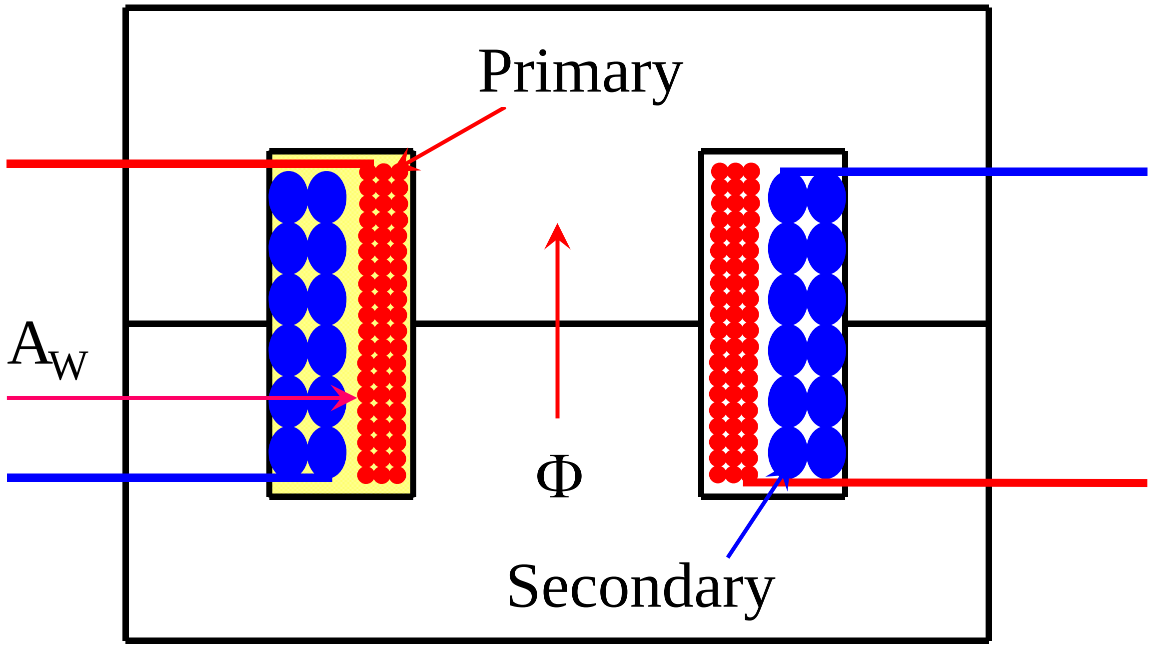
Window Space



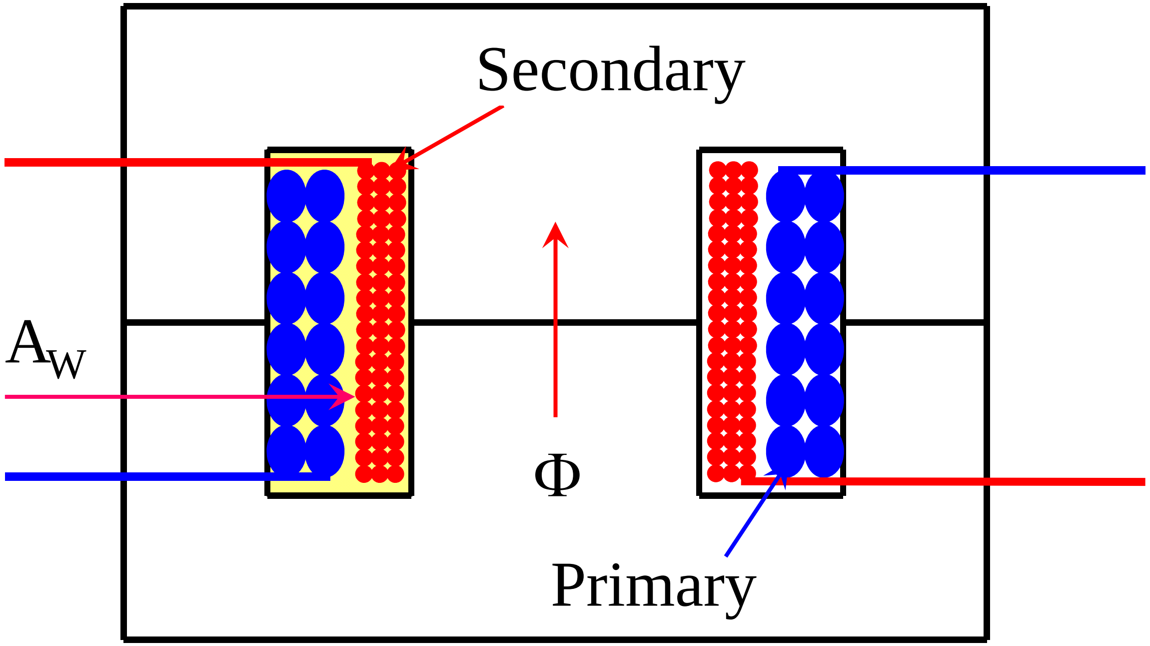
$$N_1 a_1 + N_2 a_2 = k_W A_W$$

A_W is a Function of Conductor Size & No. of Turns

Switched Mode Power Conversion

Transformers

Window Space



$$N_1 \frac{I_1(\text{rms})}{J} + N_2 \frac{I_2(\text{rms})}{J} = k_W A_W$$

A_W is a Function of rms Currents

Switched Mode Power Conversion

Transformers

Design Equations

$$V_1 = 4N_1 B_m A_C f_S$$

$V_1/2f_S$ is the Volt-Sec Integral

$2N_1 B_m A_C$ is the Flux Linkage

$$2\,N_1 \frac{I_1(\mathrm{rms})}{J} = k_W A_W$$

Primary Ampere-Turns Equal Secondary Ampere-Turns

Switched Mode Power Conversion

Transformers

Area-Product Equation

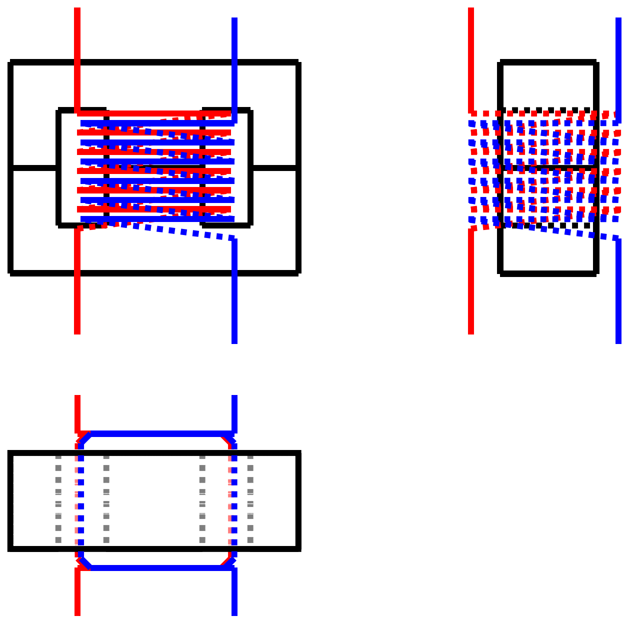
$$V_1 = 4N_1B_mA_Cf_S$$

$$2N_1\frac{I_1(\text{rms})}{J} = k_WA_W$$

$$A_CA_W = \frac{V_1I_1(\text{rms})}{2k_WB_mJf_S}$$

Switched Mode Power Conversion

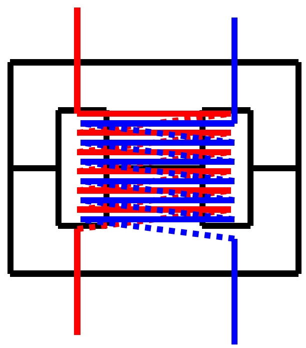
Popular Geometry (EE)

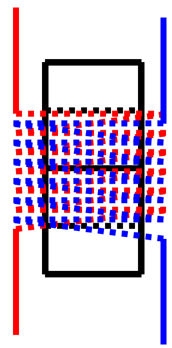


Notice the Low Reluctance (No Air Gap in the Core) Geometry

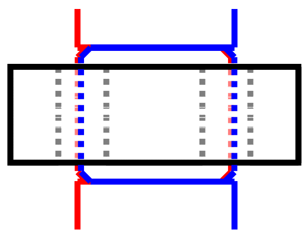
Switched Mode Power Conversion

Popular Geometry (EE)





$$L_{mp} = \frac{N_1^2}{\Re}$$



$$L_{ms} = \frac{N_2^2}{\Re}$$

On Account of Low Reluctance Magnetic Path

Magnetising Inductance is Infinity Ideally

Switched Mode Power Conversion

ETD Core Series Data

Type Number	A_C mm^2	A_W mm^2	$A_C A_W$ mm^4
ETD 29/16/10	76	128	9728
ETD 34/17/11	97	171	16587
ETD 39/20/13	125	234	29250
ETD 44/22/15	173	279	48267
ETD 49/25/16	211	343	72373
ETD 54/28/19	280	412	115360
ETD 59/31/22	368	473	174064

Standard Cores

ETD

Switched Mode Power Conversion

Few Other Geometries (EE)

Standard Cores

ETD

Low Profile Cores

EFD

Pot Cores

P

Switched Mode Power Conversion

Sample Core Selection

V_1 = 48 V ;
V_2 = 400 V ; I_2 = 3 A ;
High Frequency (50 kHz) Application

$$A_C A_W = \frac{400 * 3 * 10^{12}}{2 * 0.35 * 0.2 * 3 * 10^6 * 50000} = 57142 \text{ mm}^4$$

Switched Mode Power Conversion

ETD Core Series Data

Type Number	A_C mm^2	A_W mm^2	$A_C A_W$ mm^4
ETD 29/16/10	76	128	9728
ETD 34/17/11	97	171	16587
ETD 39/20/13	125	234	29250
ETD 44/22/15	173	279	48267
ETD 49/25/16	211	343	**72373**
ETD 54/28/19	280	412	115360
ETD 59/31/22	368	473	174064

Select ETD 49/25/16

N67 Material

Switched Mode Power Conversion

No. of Turns

Type Number	A_C mm^2	A_W mm^2	$A_C A_W$ mm^4
ETD 49/25/16	211	343	72373
N_1	**6**		
N_2	**47**		

$$N = \frac{V}{4B_m A_C f_S} = \frac{48}{4*0.2*211*10^{-6}*50000}$$

Select N_1 = 6 Turns ; N_2 = 47 Turns

Switched Mode Power Conversion

Wire Size

Type Number	A_C mm^2	A_W mm^2	A_CA_W mm^4
ETD 49/25/16	211	343	72373
N_1	6		
N_2	47		
a_1	**8.33 mm^2**		
a_2	**1 mm^2**		

$$a_{W2} = \frac{3}{3} = 1\ \mathrm{mm}^2 \qquad a_{W1} = 8.33\ \mathrm{mm}^2$$

Switched Mode Power Conversion

Wire Size – Skin Effect

Type Number	A_C mm^2	A_W mm^2	A_CA_W mm^4
ETD 49/25/16	211	343	72373
N_1	6		
N_2	47		
a_1	**8.33 mm^2**		
a_2	**1 mm^2**		

$$\text{Skin Depth} = \frac{1}{\sqrt{\pi\mu\sigma f}}$$

$$\mu = 4\pi 10^{-7} \, H/m \qquad \sigma = 59.6 \; 10^{6} \, /\Omega - m$$

For Copper @50 kHz, Skin Depth = 0.29 mm : 0.26 mm^2 (24 SWG)

Switched Mode Power Conversion

Primary & Secondary Conductors

Type Number	A_C mm^2	A_W mm^2	$A_C A_W$ mm^4
ETD 49/25/16	211	343	72373
N_1	6		
N_2	47		
a_1	**8.33 mm^2**		
a_2	**1 mm^2**		

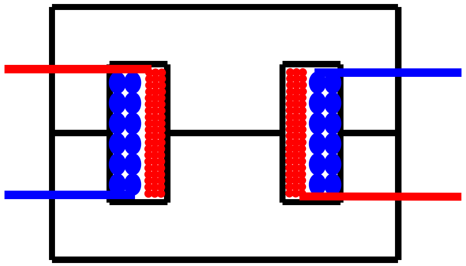
For Secondary 4 wires of 24 SWG in Parallel

For Primary 32 wires of 24 SWG in Parallel

Switched Mode Power Conversion

Transformers

Parasitic Resistance



Mean Length of a Turn: 83 mm

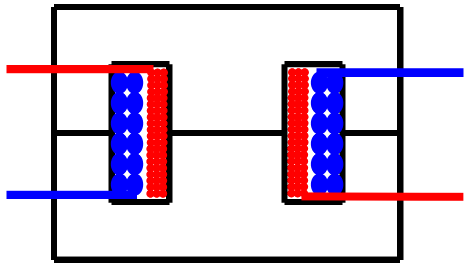
Primary Resistance: 10 μΩ

Secondary Resistance: 629 μΩ

Switched Mode Power Conversion

Transformers

Core Loss



Loss at 0.2 T at 100 kHz: 15.5 W

Loss at 0.2 T at 50 kHz: 7.75 W

Core Loss Resistance: 297 Ω

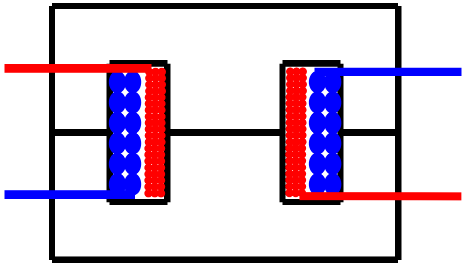
ETD 49/25/16

N67 Material

Switched Mode Power Conversion

Transformers

Magnetising Inductance



le = 114 mm ; A_C = 211 mm^2 ; μ_r = 1590

Reluctance = 270405 /H

Primary Inductance: 0.133 mH

Secondary Inductance: 8.17 mH

Switched Mode Power Conversion

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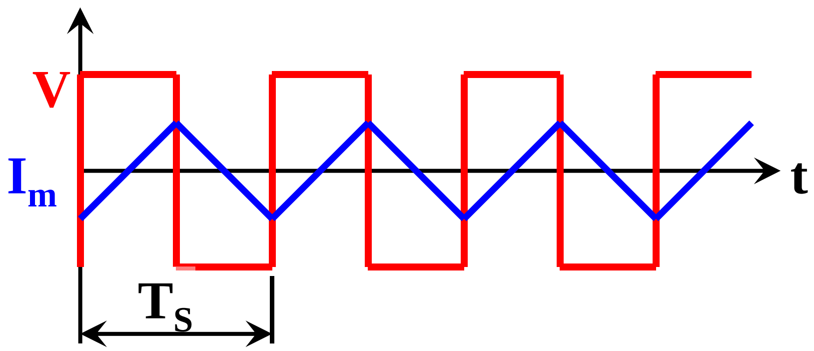
Primary Magnetising Current Peak



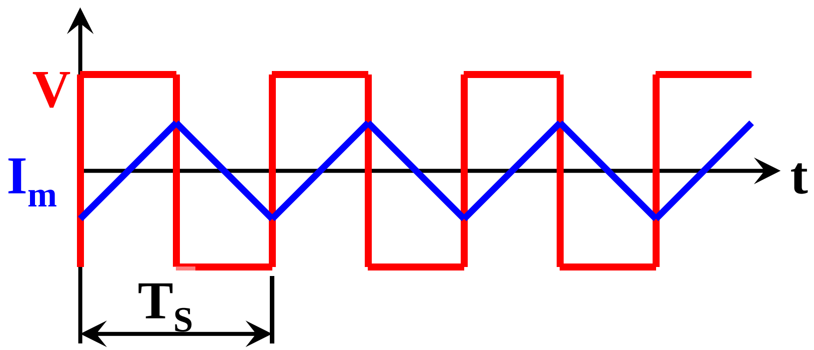
$$I_m(\text{peak}) = \frac{48}{2*0.133\,\text{m}}10\,\mu = 1.8\,\text{A}$$

Magnetising Current Peak << Primary Current

Switched Mode Power Conversion

Transformers

Stored Energy in the Core



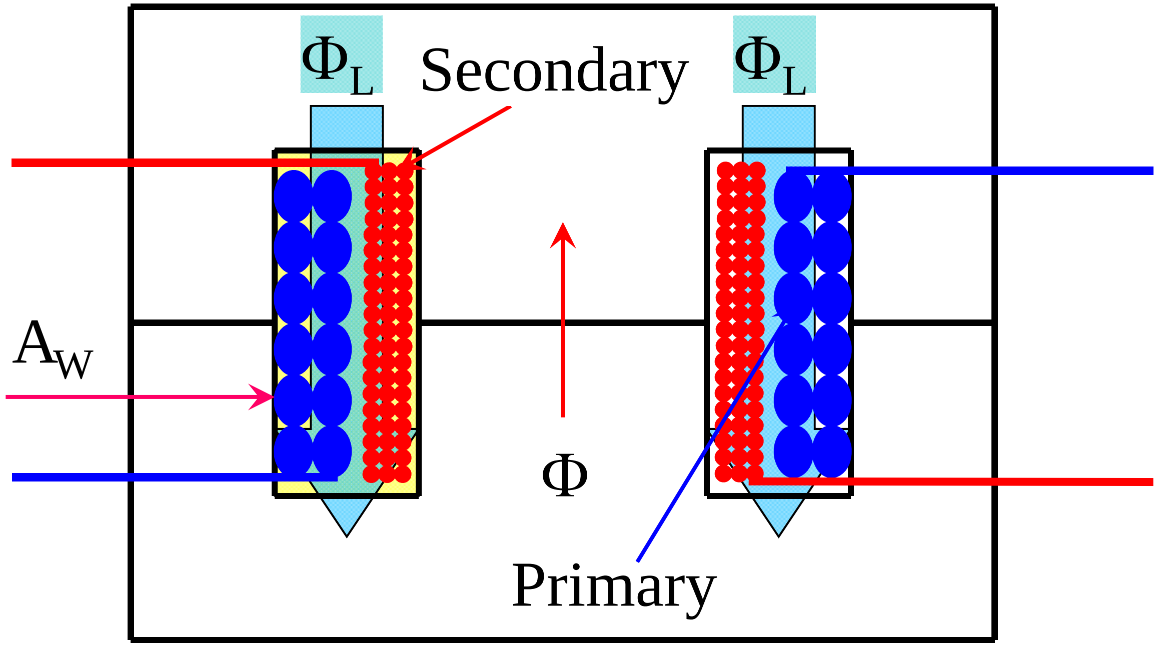
$$E_m = \frac{L_m}{2} I_m^2 = 0.5 * 0.133\text{m} * 1.8^2 = 0.22 \text{ mJ}$$

Stored Energy in the Core = 0.22 mJ

Switched Mode Power Conversion

Transformers

Leakage Energy in the Window

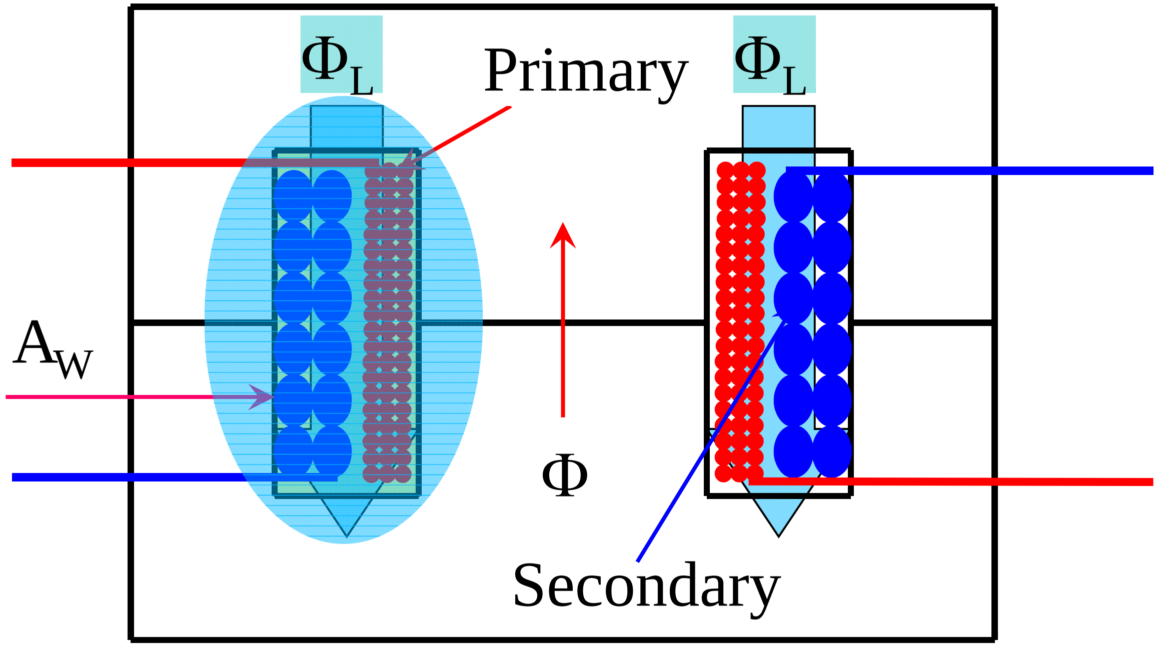


Leakage is Another Non-ideality in the Magnetic Circuit

Switched Mode Power Conversion

Transformers

Leakage Energy in the Window



Leakage is Another Non-ideality in the Magnetic Circuit

Switched Mode Power Conversion

Transformers

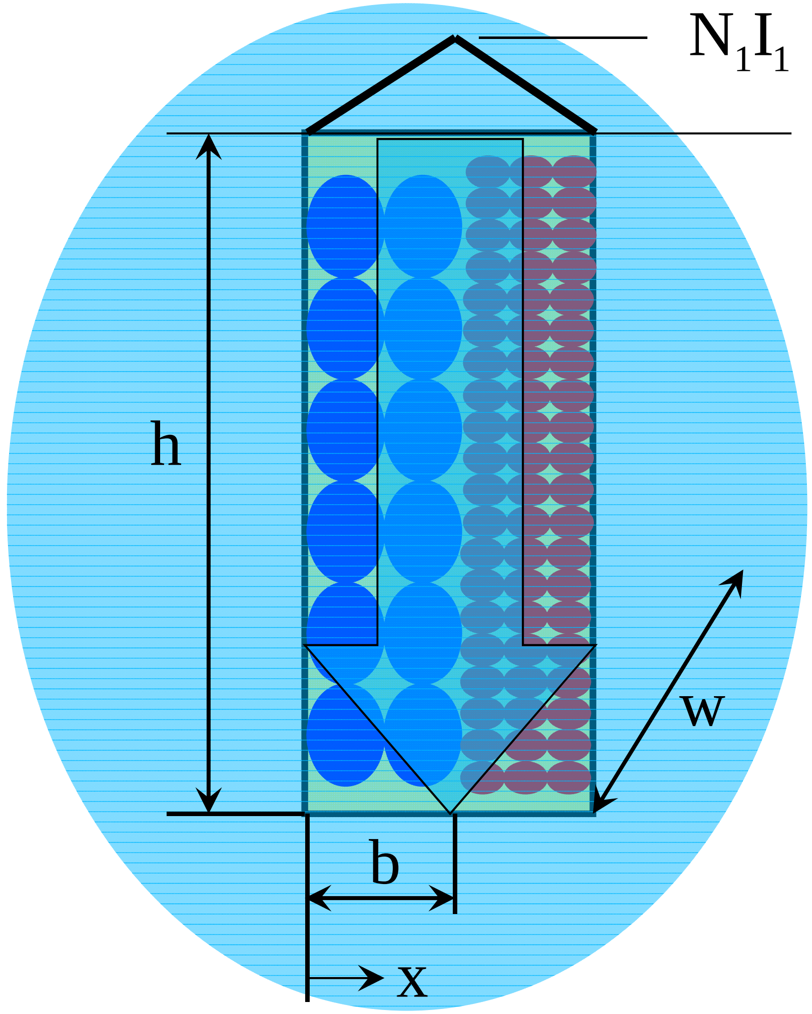
Leakage Energy in the Window

$$H(x) = \frac{N_1 I_1}{h} \frac{x}{b}$$

$$B(x) = \frac{\mu_o N_1 I_1}{h} \frac{x}{b}$$

$$L_\ell = \frac{\mu_o}{I_1^2} \iiint H^2(x)\, dv$$

$$dv = 2\, h\, w\, dx$$



Switched Mode Power Conversion

Transformers

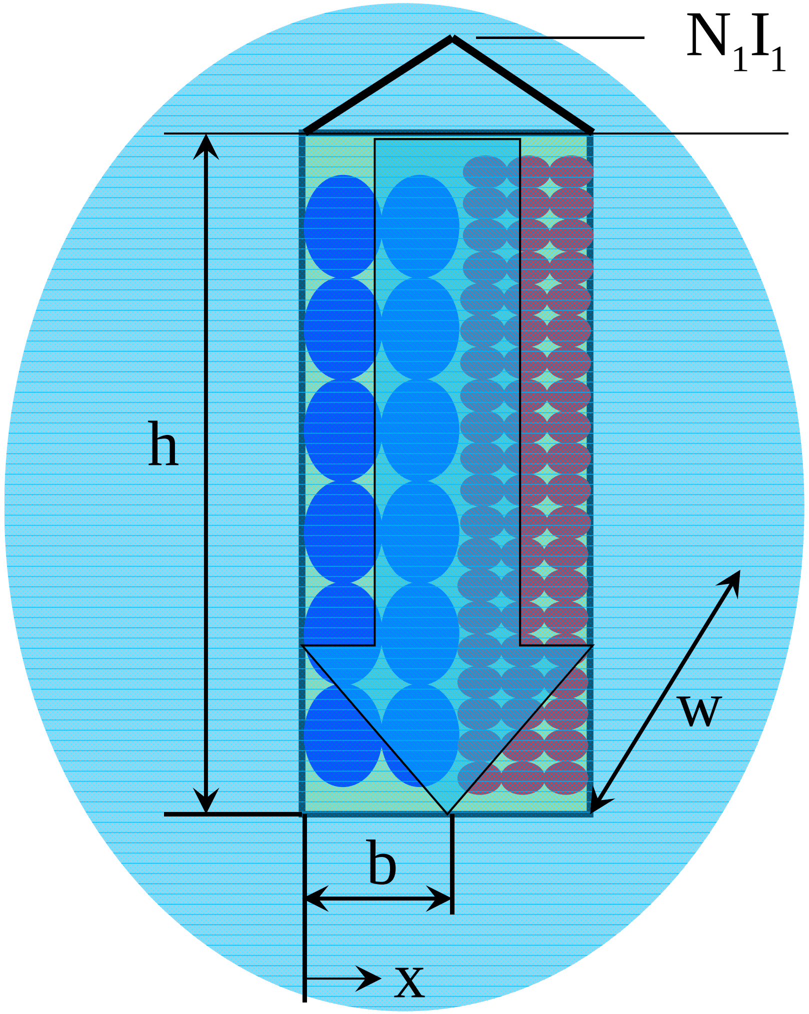
Leakage Energy in the Window

$$L_\ell = \frac{\mu_o N_1^2}{h^2}\frac{2}{b^2}\, h\, w \int_0^b x^2\, dx$$

$$L_\ell = \frac{2\mu_o N_1^2\, b\, w}{3*h}$$

0.07 μH << 133 μH

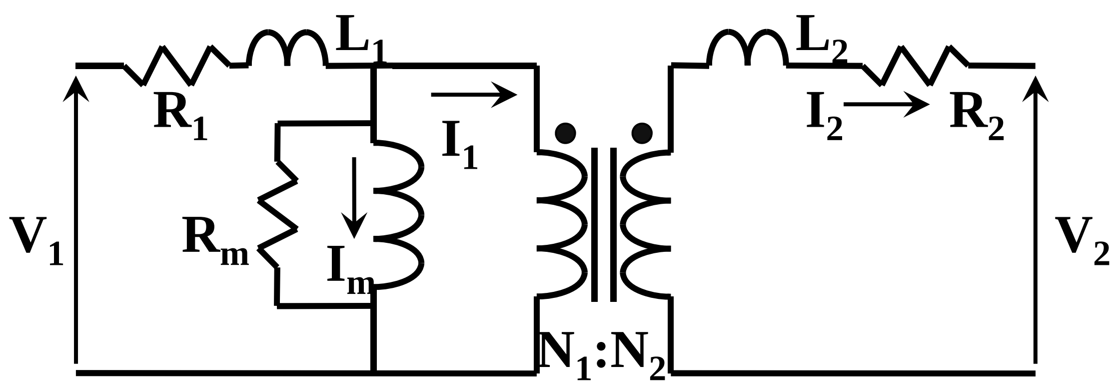
L_{pu} = 6.1 μH



Switched Mode Power Conversion

Transformers

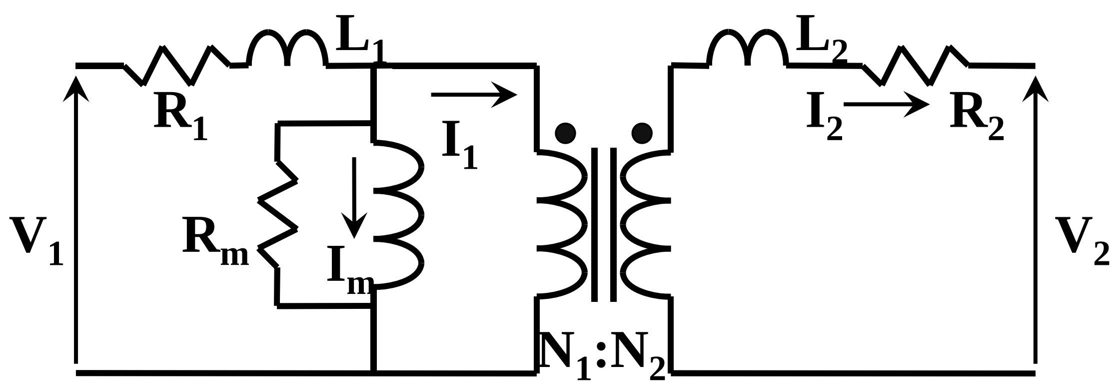
Circuit Model with Dominant Non-idealities



Switched Mode Power Conversion

Transformers

Measurement of Circuit Parametes



Open Circuit & Short Circuit Test

Switched Mode Power Conversion

Transformers

Devices for Efficient Power Conversion

Switches

Inductors

Transformers

Capacitors

Switched Mode Power Conversion

Capacitors

Devices for Efficient Power Conversion

Switches
Inductors
Transformers
Capacitors