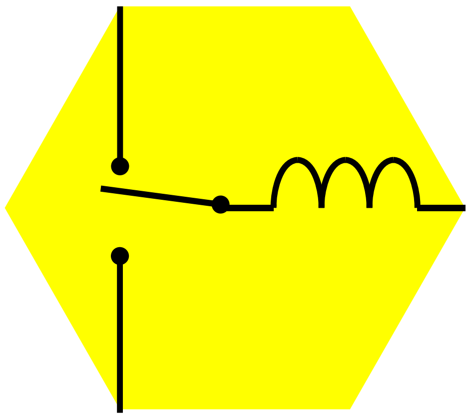
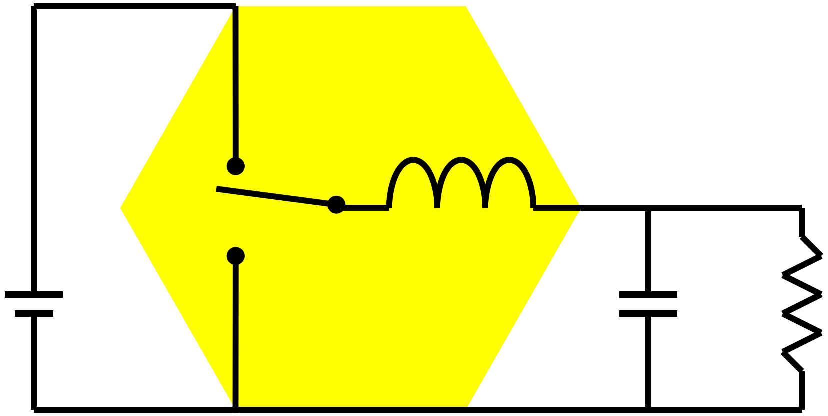
Switched Mode Power Conversion



Basic Converter Cell

Switched Mode Power Conversion

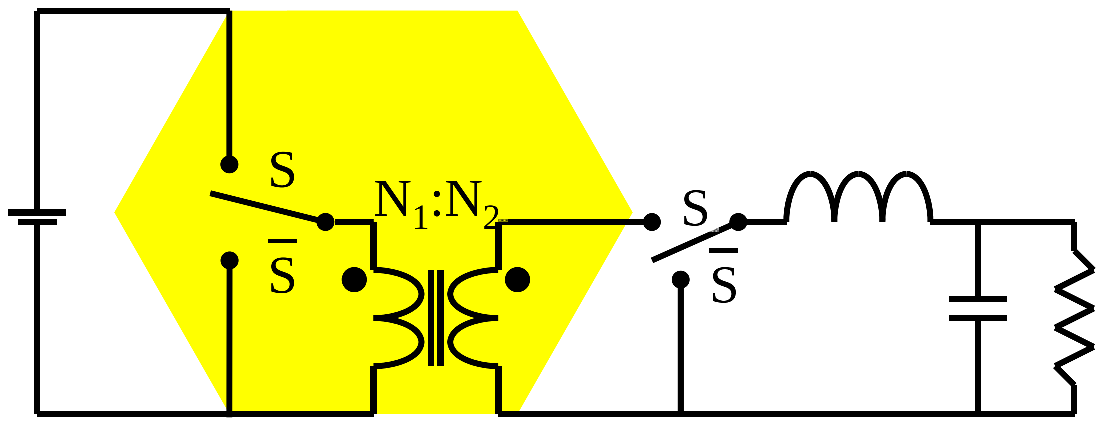
Non-Isolated Converter



Buck Converter

Switched Mode Power Conversion

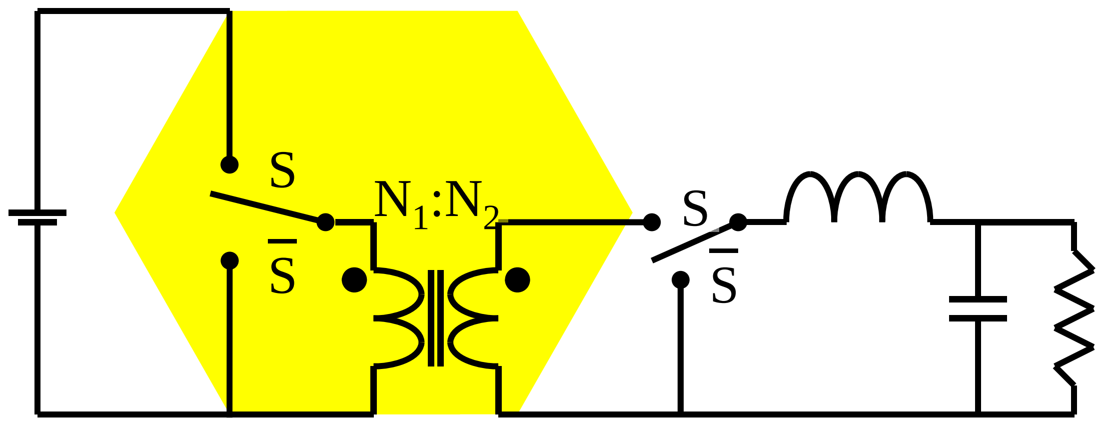
Isolated Converters



Electromagnetic Isolation

Switched Mode Power Conversion

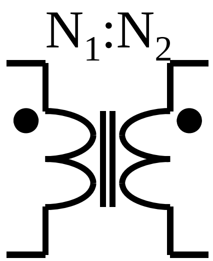
Isolated Converters



Important Issue – Flux Balance

Switched Mode Power Conversion

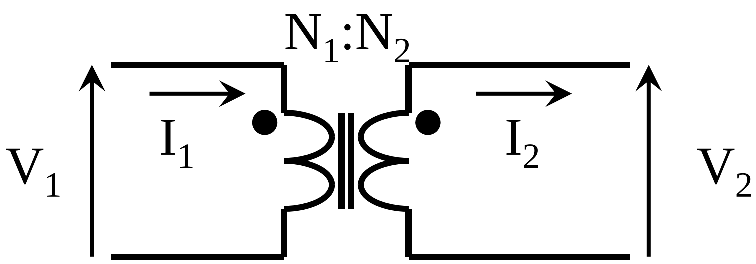
Isolated Converters



Review of Magnetic Circuits

Switched Mode Power Conversion

Isolated Converters



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

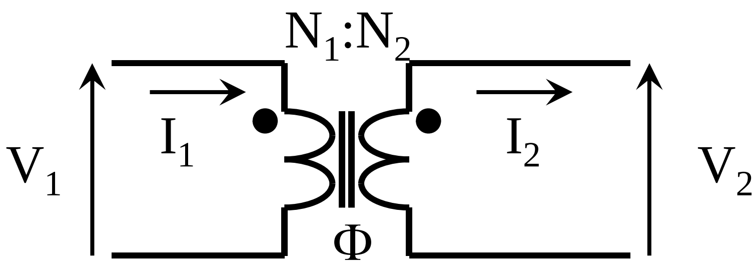
V – I Relationships

Switched Mode Power Conversion

Isolated Converters

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

$$V_1 = N_1\frac{d\Phi}{dt}$$



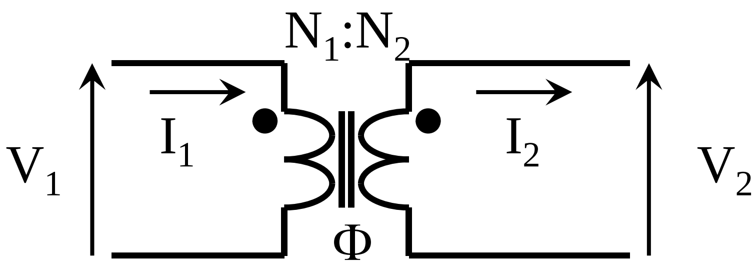
$$V_2 = N_2\frac{d\Phi}{dt}$$

V – Φ Relationship

Switched Mode Power Conversion

Isolated Converters

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



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt = \frac{1}{N_2}\int_0^t V_2\,dt$$

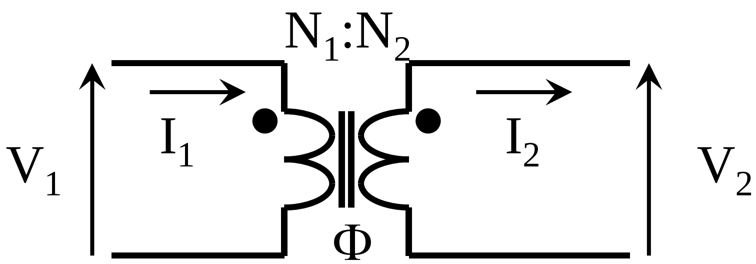
Φ – V Relationship

Switched Mode Power Conversion

Isolated Converters

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

$$V_1 = N_1\frac{d\Phi}{dt}$$



$$V_2 = N_2\frac{d\Phi}{dt}$$

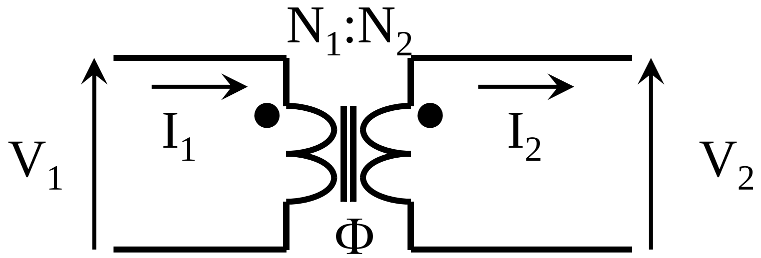
$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt = \frac{1}{N_2}\int_0^t V_2\,dt$$

For Periodic Operation with Stable Flux Swing: $\int_0^{T_S} V\,dt = 0$

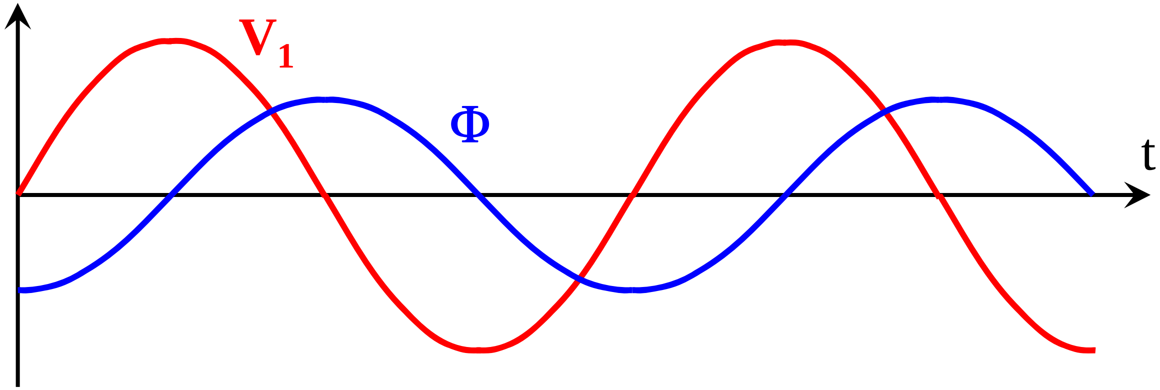
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\, dt$$

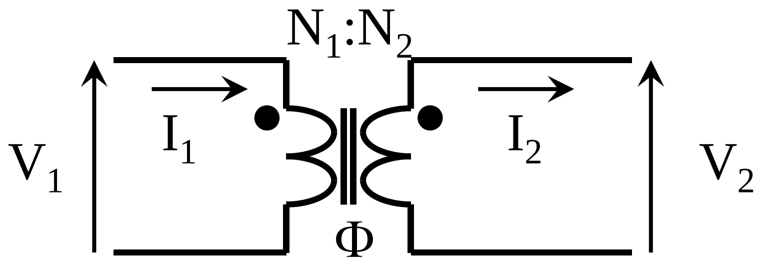


Sinusoidal Excitation: $V_1 = V\,\mathrm{Sin}(\omega t)$

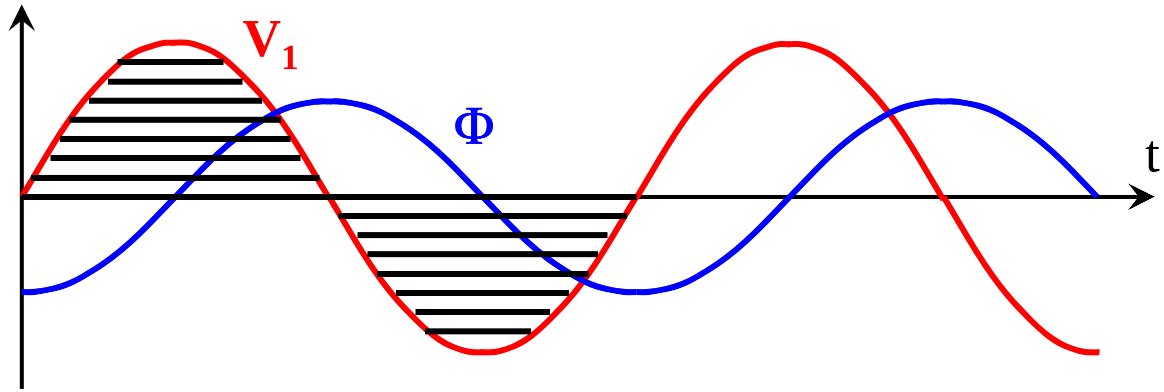
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1} \int_0^t V_1 \, dt$$



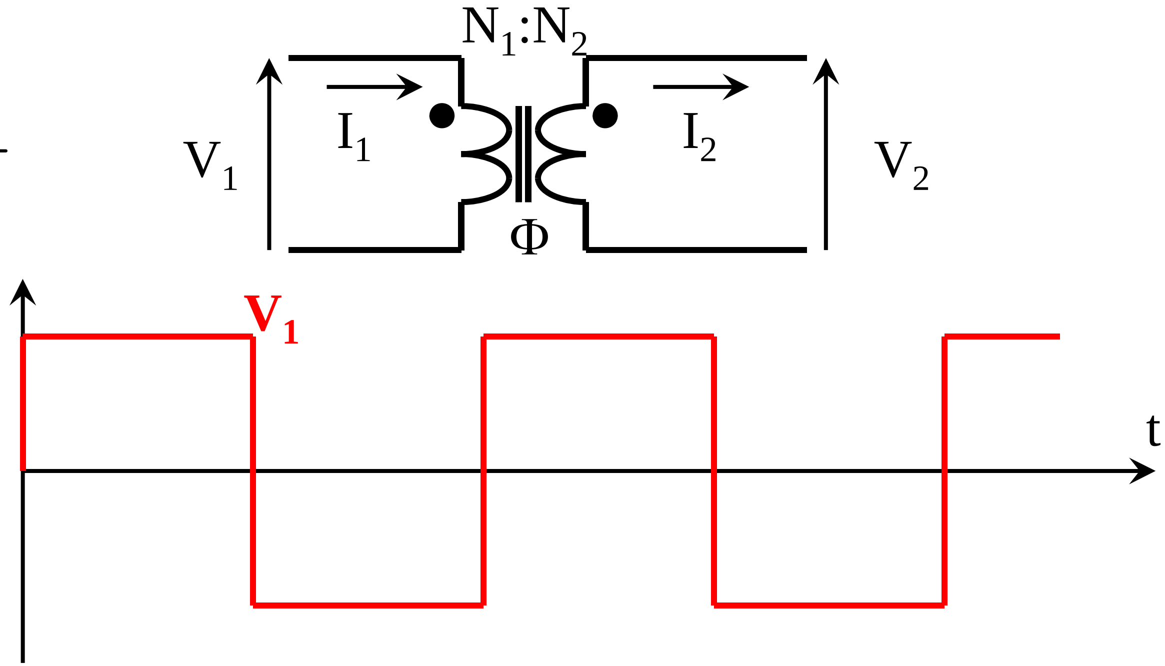
$$\int_0^{T_S} V_1 \, dt = 0$$

Average Excitation Voltage = 0

Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$

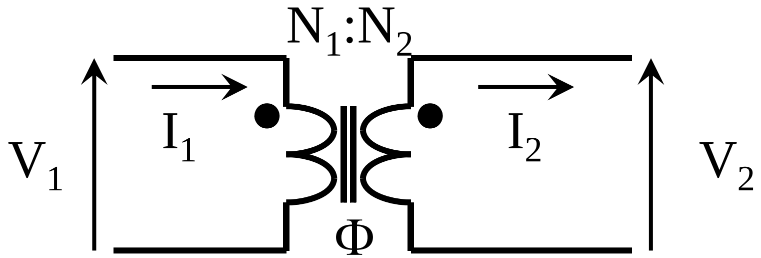


SMPC Transformers Encounter Square Wave Voltages

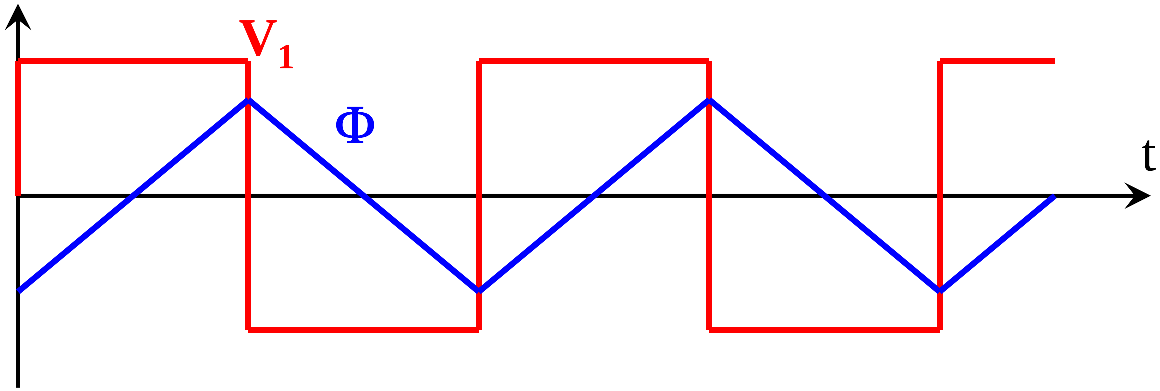
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$$

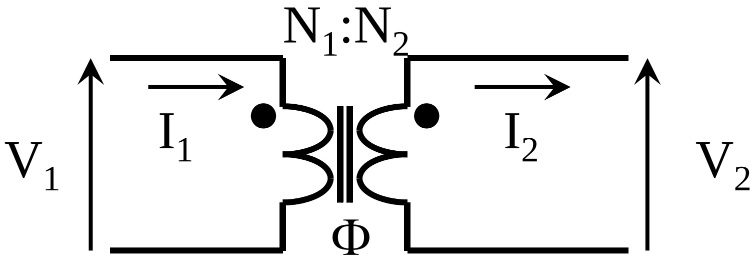


Flux is the Integral of the Voltage: Triangular

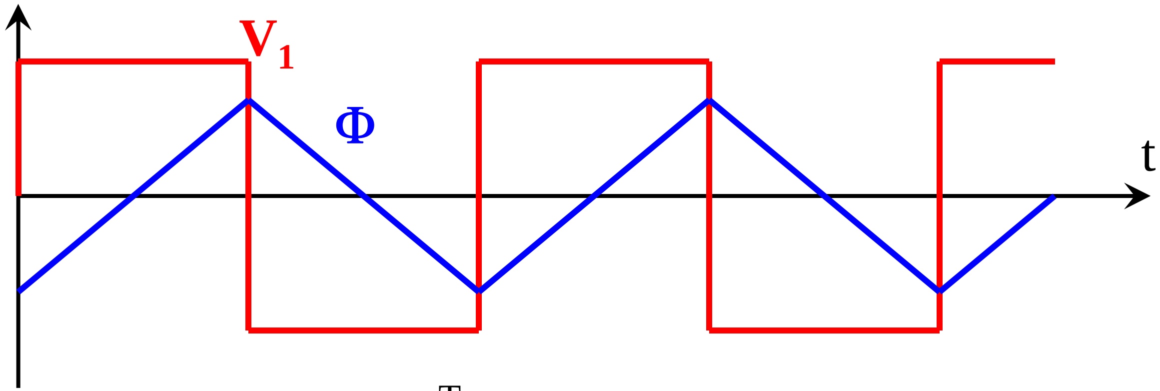
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1 \, dt$$



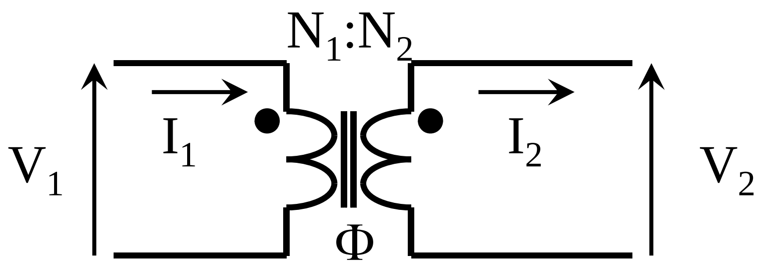
$$\int_0^{T_S} V_1 \, dt = 0$$

When Average Voltage is Zero, Flux Swing Is Symmetric and Stable

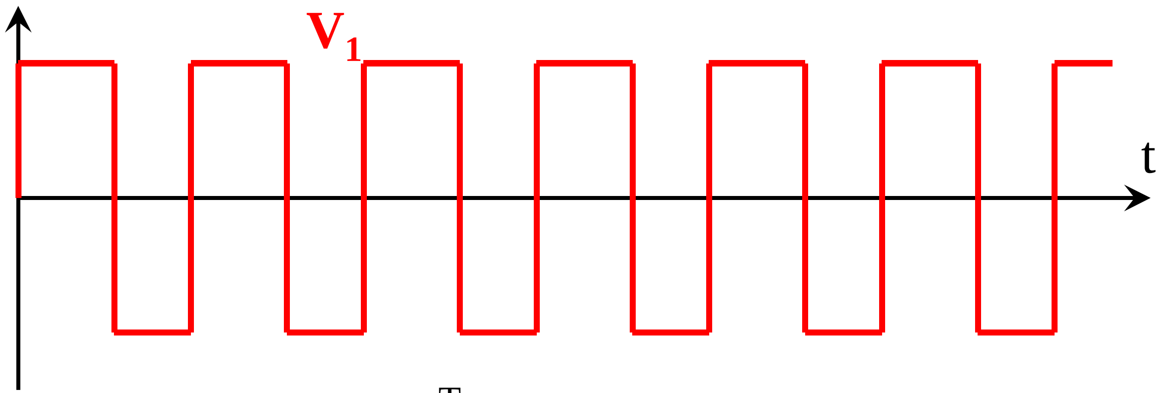
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$$



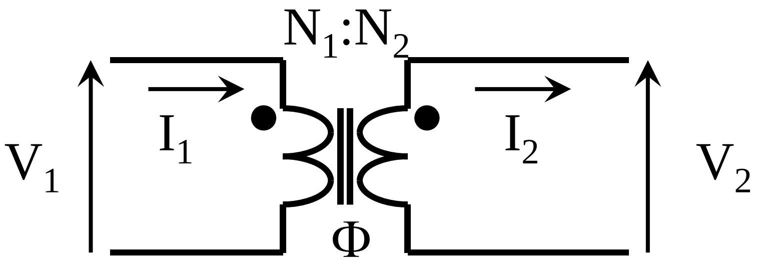
$$\int_0^{T_S} V_1\,dt \neq 0$$

When Average Voltage is not Zero ..

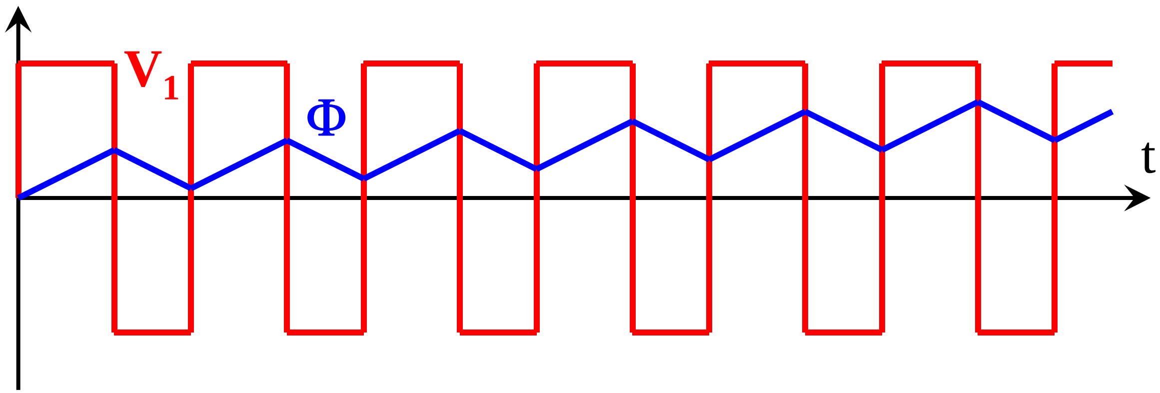
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\, dt$$

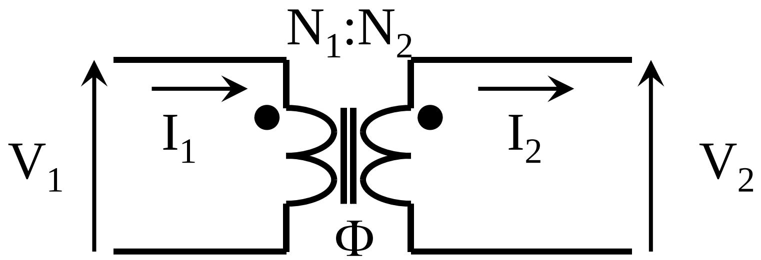


When Average Voltage is not Zero, Flux Builds up Asymmetrically.

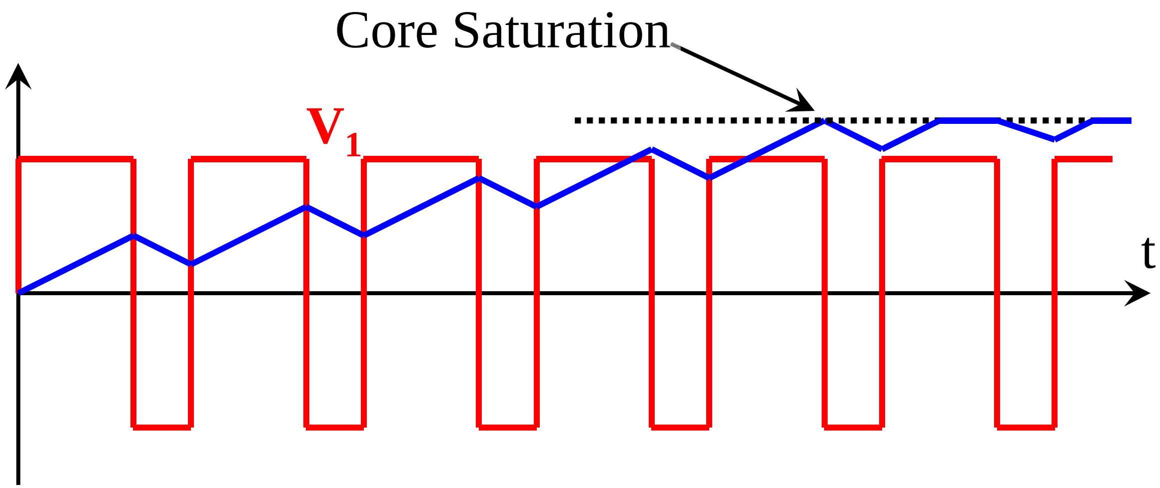
Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$



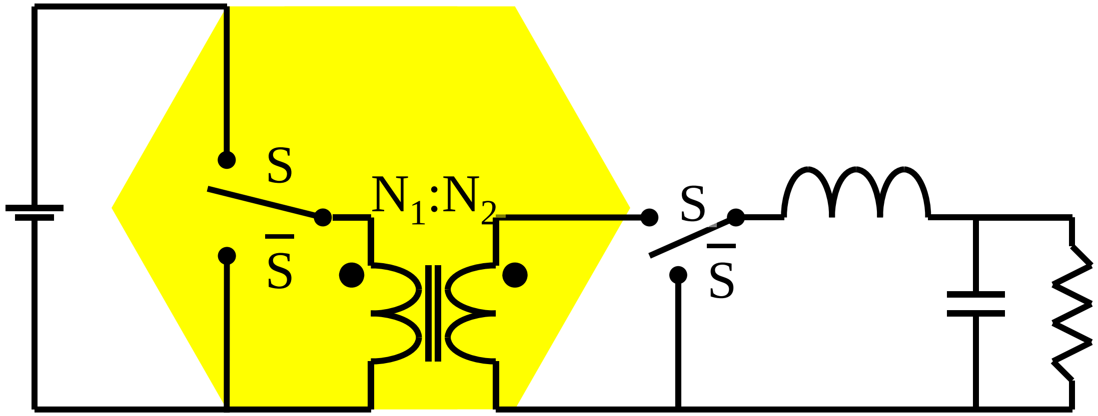
$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\, dt$$



.. Flux Builds up in the Core Asymmetrically and the Core Walks into Saturation Eventually.

Switched Mode Power Conversion

Isolated Converters



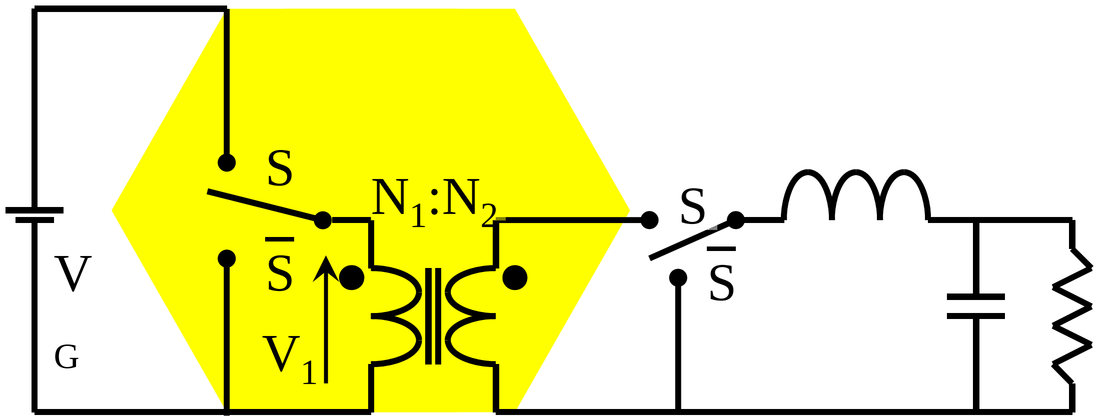
$$T_{ON}: S \text{ on}; V_1 = V_G$$

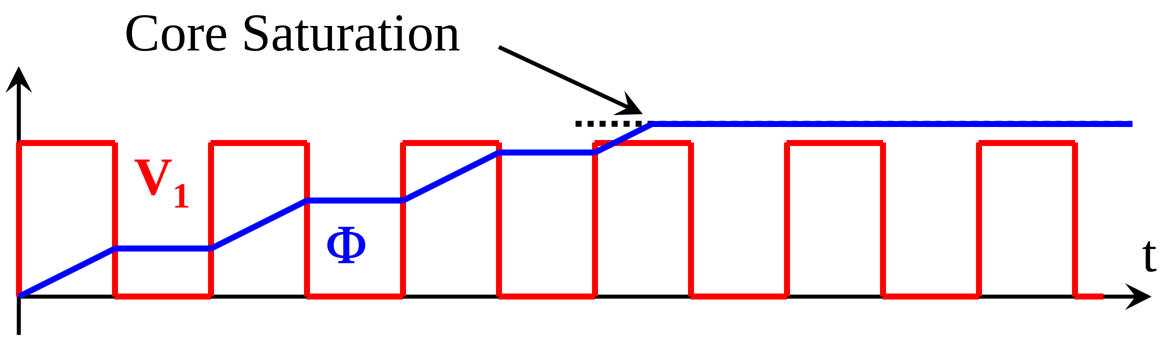
$$T_{OFF}: \overline{S} \text{ on}; V_1 = 0$$

Notice the Asymmetric Voltage in Transformer Excitation

Switched Mode Power Conversion

Isolated Converters

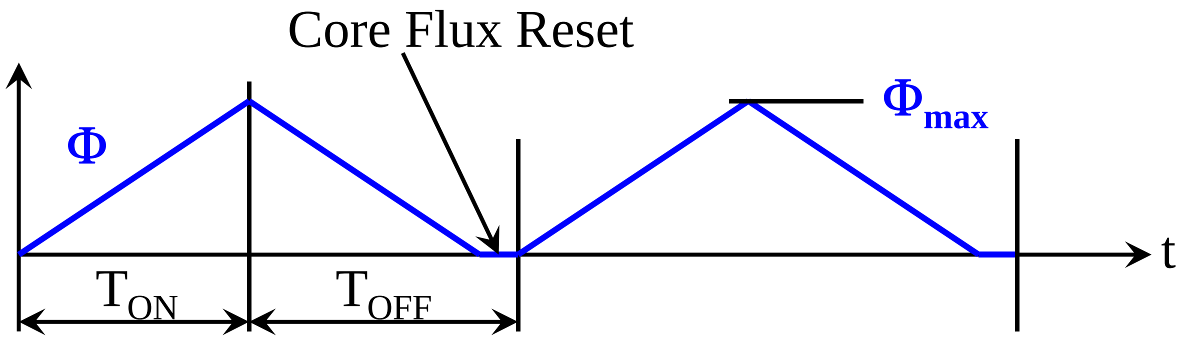




Notice the Core Flux Build-up

Switched Mode Power Conversion

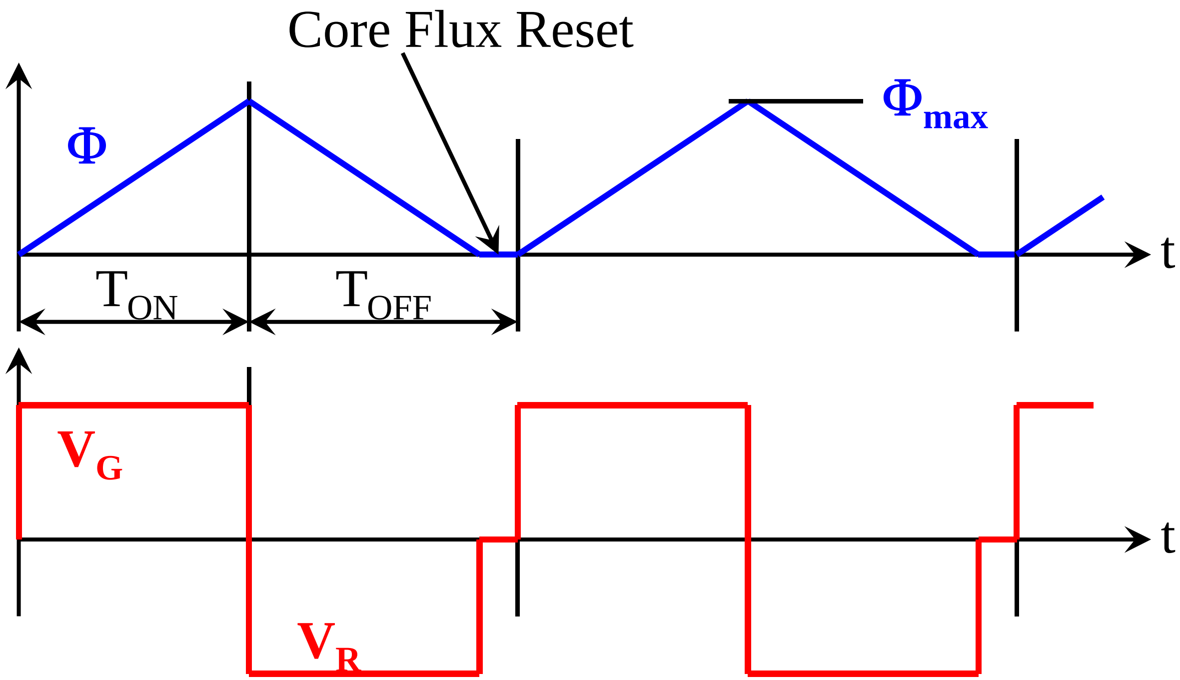
Isolated Converters



Core Flux has to be set back to zero in every cycle

Switched Mode Power Conversion

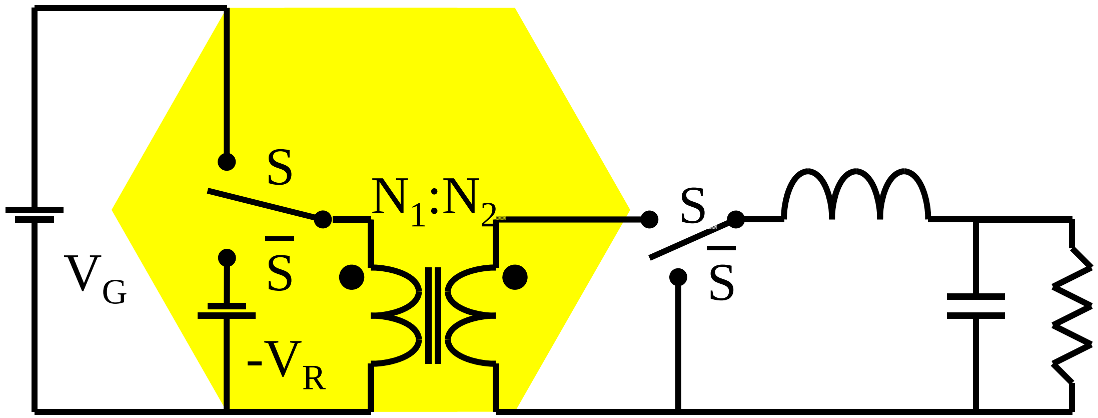
Isolated Converters



Appropriate reset process has to be introduced

Switched Mode Power Conversion

Isolated Converters



$$T_{ON} : S \text{ on}; V_1 = V_G$$

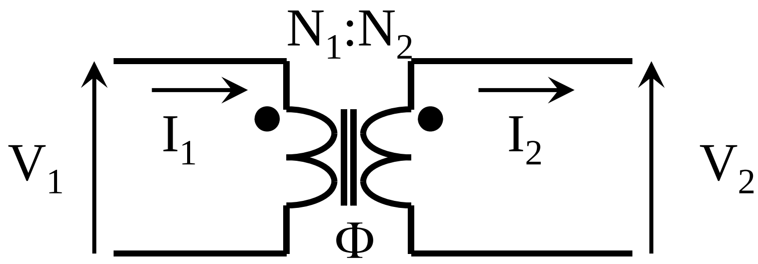
$$T_{OFF} : \overline{S} \text{ on}; V_1 = -V_R$$

Notice the reset voltage $-V_R$

Switched Mode Power Conversion

Isolated Converters

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



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

$$\text{Magnetising Ampere – Turns} : \left(N_1 I_1 - N_2 I_2\right)$$

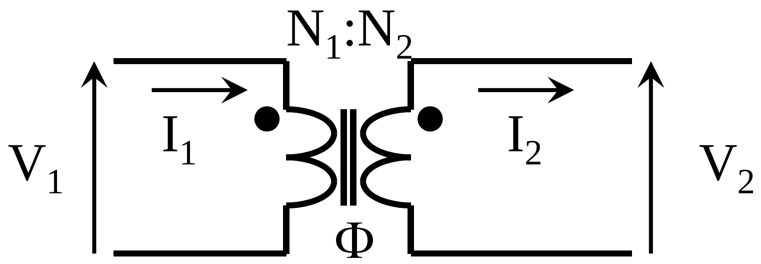
$$\text{Magnetising Current (referred to Primary)} : \frac{\left(N_1 I_1 - N_2 I_2\right)}{N1}$$

Magnetising Current

Switched Mode Power Conversion

Isolated Converters

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



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

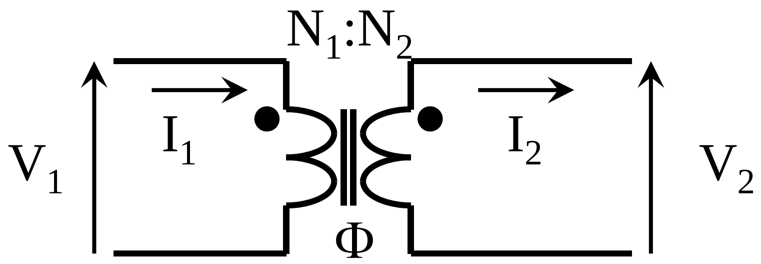
$$\Phi = \frac{\left(N_1 I_1 - N_2 I_2\right) \mu A_C}{l_C}$$

Φ – I Relationships

Switched Mode Power Conversion

Isolated Converters

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



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

$$I_m : \frac{\left(N_1 I_1 - N_2 I_2\right)}{N1}$$

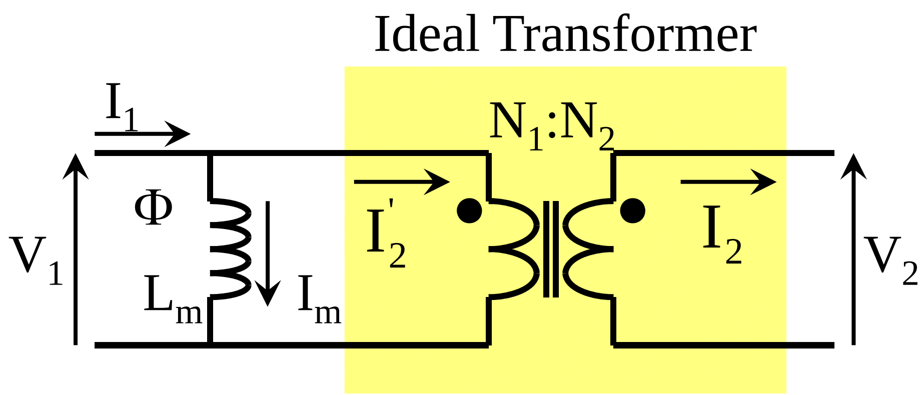
$$L_m I_m = N_1 \Phi = N_1 \frac{\left(N_1 I_1 - N_2 I_2\right) \mu\, A_C}{l_C} = \frac{N_1^2 \mu\, A_C}{l_C} I_m$$

$$L_m = \frac{N_1^2 \mu\, A_C}{l_C}$$

Magnetising Inductance L_m

Switched Mode Power Conversion

Isolated Converters

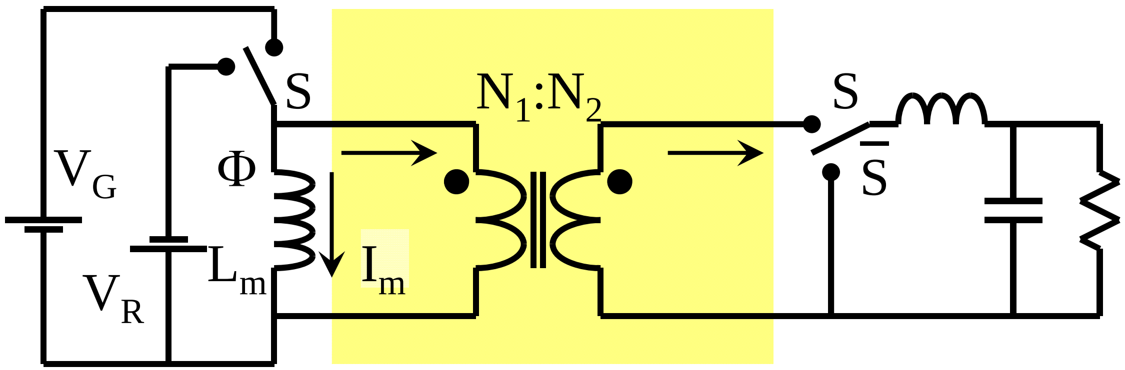


Magnetising Current is represented as a Shunt Non-ideality to the Transformer

Equivalent Circuit

Switched Mode Power Conversion

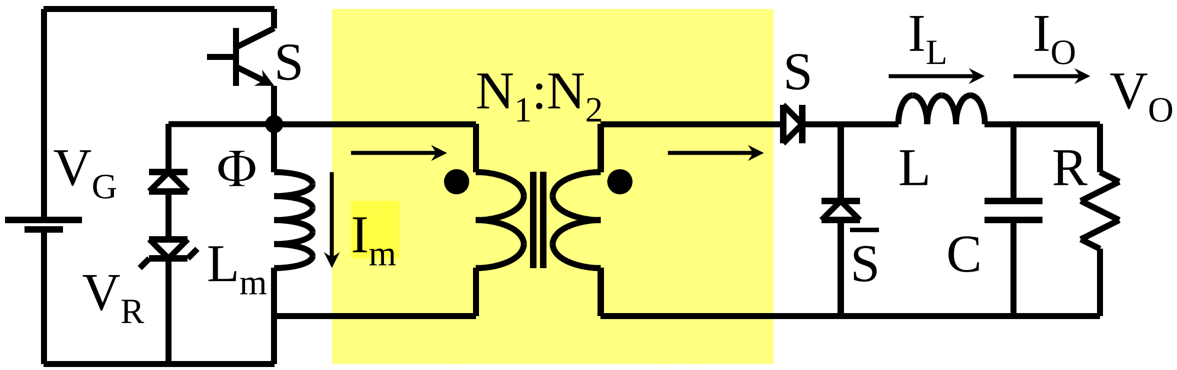
Forward Converter



Forward Converter

Switched Mode Power Conversion

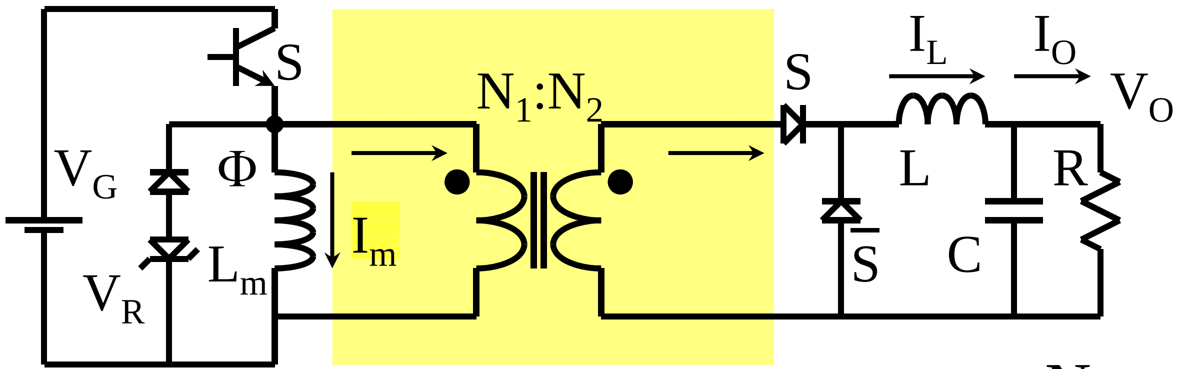
Forward Converter

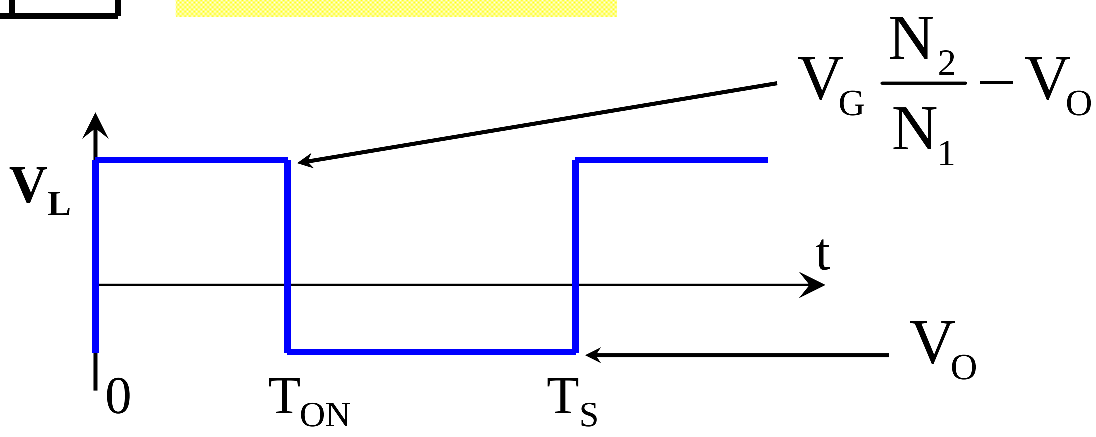


Forward Converter – Circuit Realisation

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

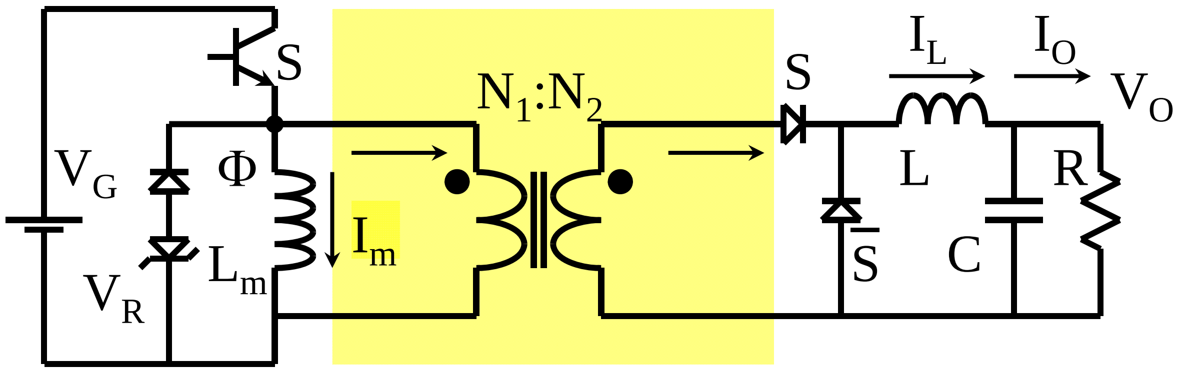




Volt – Sec Balance on Filter L

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



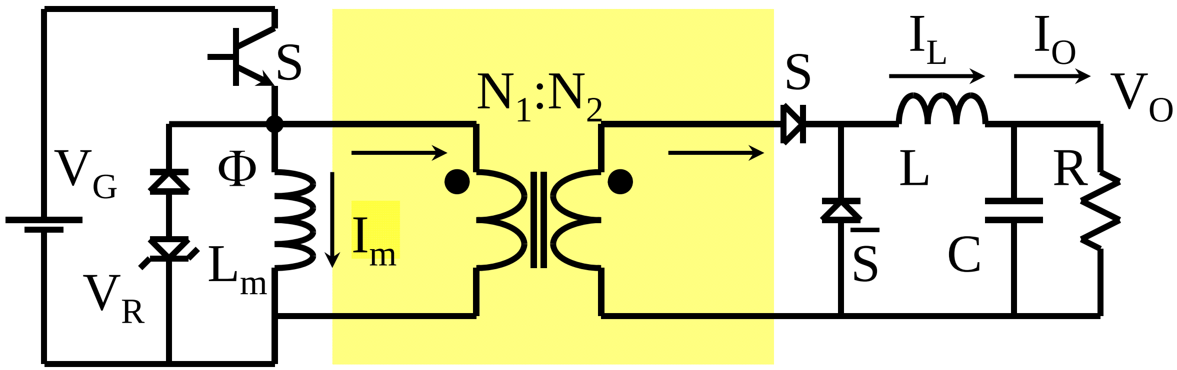
$$\left(V_G \frac{N_2}{N_1} - V_O \right) T_{ON} - V_O T_{OFF} = 0$$

$$\frac{V_O}{V_G} = \frac{N_2}{N_1} D$$

Volt – Sec Balance on Filter L

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



$$I_G = D\frac{N_2}{N_1} I_O$$

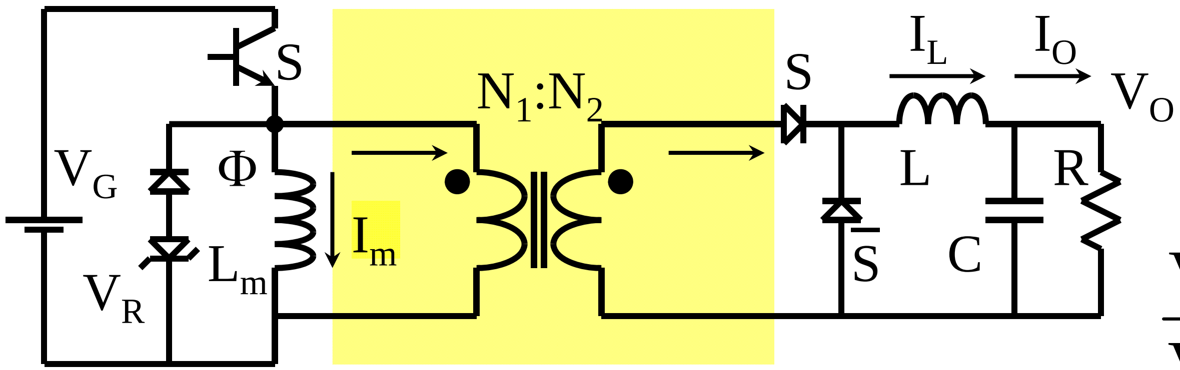
$$\frac{I_G}{I_O} = D\frac{N_2}{N_1}$$

Ideal Current Ratio – I_m is neglected

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\frac{I_G}{I_O} = D\frac{N_2}{N_1}$$



$$\frac{V_O}{V_G} = \frac{N_2}{N_1}D$$

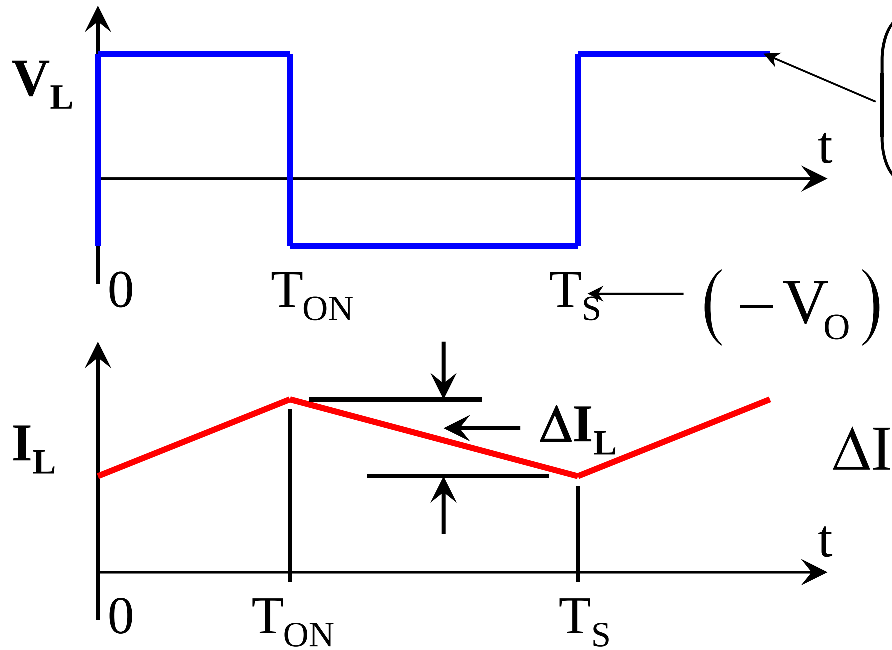
$$\frac{V_O I_O}{V_G I_G} = \frac{N_2}{N_1} D \frac{N_1}{N_2}\frac{1}{D} = 1$$

Ideal Efficiency

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\left(V_G \frac{N_2}{N_1} - V_O \right)$$



$$I_L = \frac{V_O}{R}$$

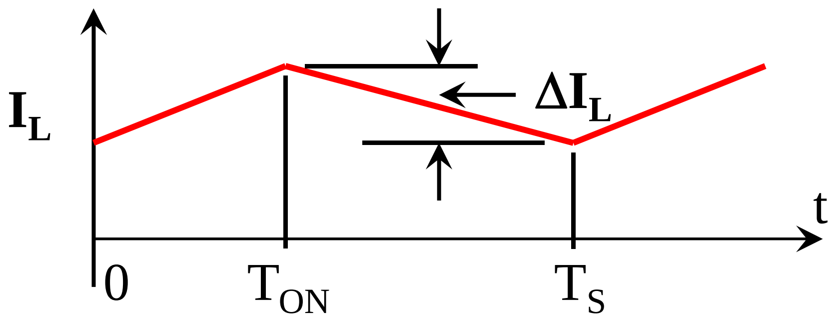
$$\Delta I_L = \frac{V_O}{L}(1-D)T_S$$

$$\frac{\Delta I_L}{I_L} = (1-D)\frac{T_S}{(L/R)}$$

Inductor Ripple Current

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



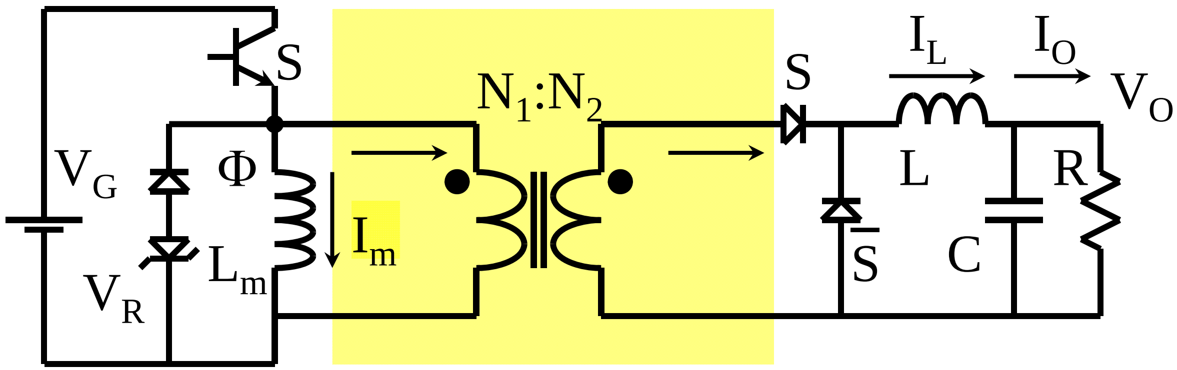
$$\frac{\Delta I_L}{I_L} = \frac{(1-D)}{(L/R)} T_S \qquad\qquad T_S \ll \frac{L}{R}$$

Condition for Low Ripple Current

Switching Period T_S << Circuit Time Constant (L/R)

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



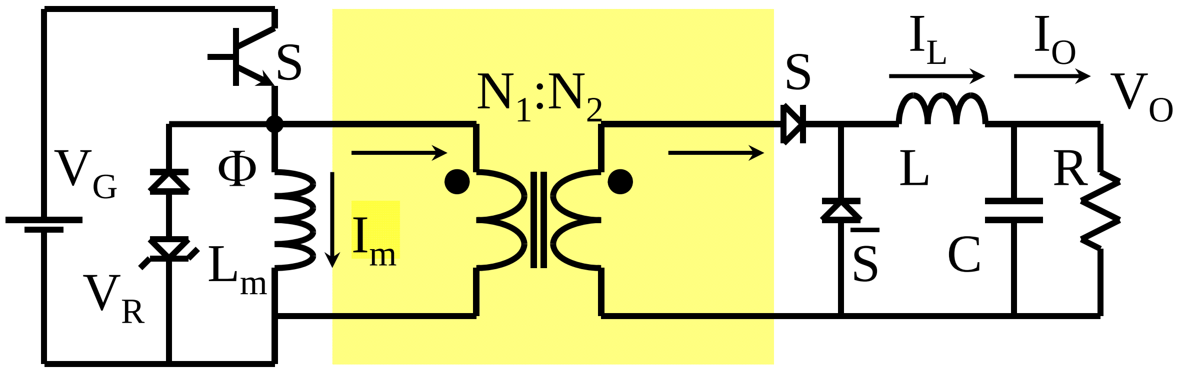
$$\left[\left(V_G - V_T\right)\frac{N_2}{N_1} - V_D - V_O\right] DT_S - \left(V_D + V_O\right)(1-D)T_S = 0$$

$$V_G D \frac{N_2}{N_1}\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OI}}\right) = V_O$$

Non-Ideality of the Switches

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

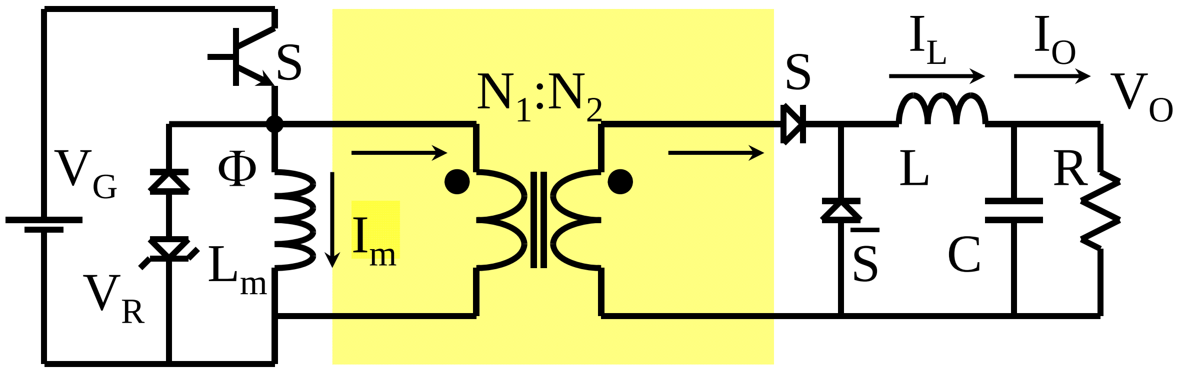


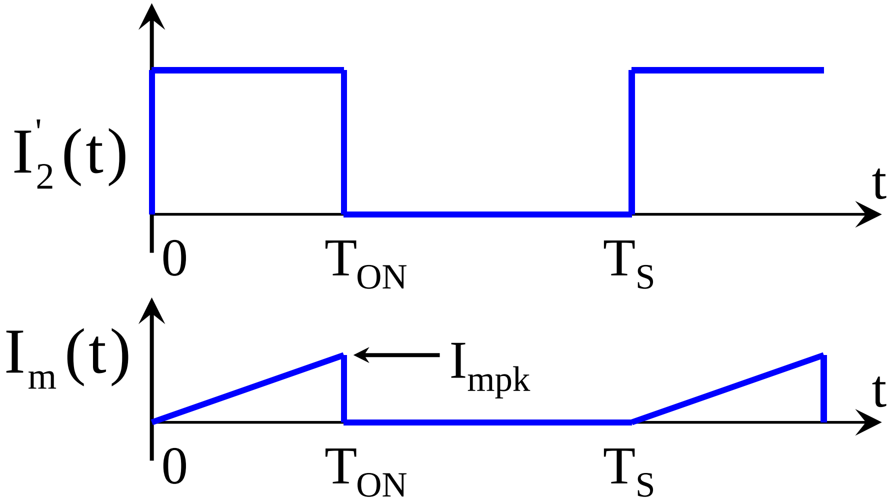
$$\frac{V_O}{V_G} = D\,\frac{N_2}{N_1}\left(1-\frac{V_T}{V_G}-\frac{V_D}{V_{OI}}\right)$$

Non-Ideality of the Switches

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



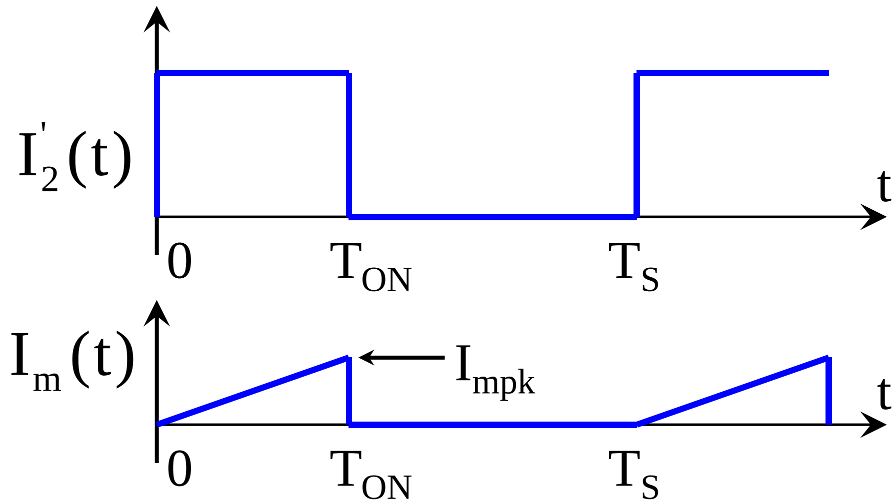


$$I_{mpk} = \frac{V_G D T_S}{L_m}$$

Current Conversion Ratio

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



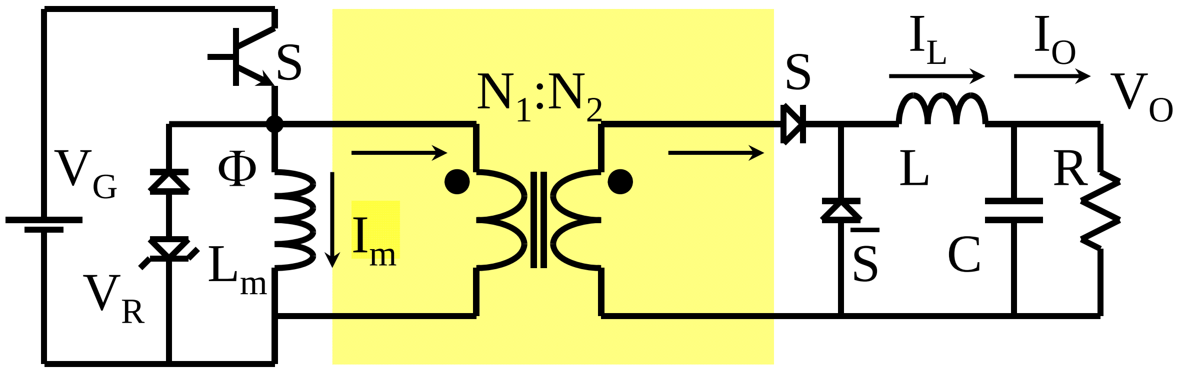
$$I_G = I_O \frac{N_2}{N_1} D + \frac{I_{mpk}}{2} D$$

$$\frac{I_G}{I_O} = \frac{N_2}{N_1} D \left(1 + \frac{N_1}{N_2} \frac{V_G D T_S}{2 L_m I_O}\right)$$

Current Conversion Ratio

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



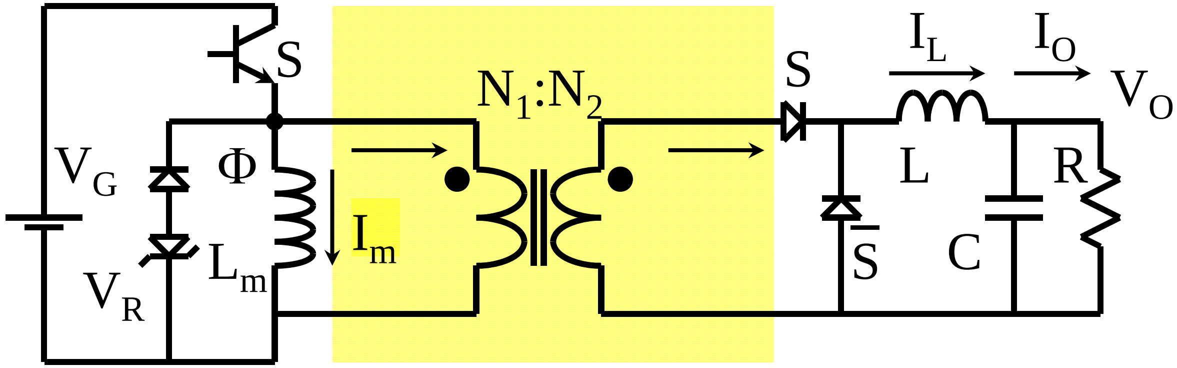
$$\frac{V_O}{V_G} = D\frac{N_2}{N_1}\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OI}}\right)$$

$$\frac{I_G}{I_O} = \frac{N_2}{N_1} D\left(1 + \frac{N_1}{N_2}\frac{V_G D T_S}{2L_m I_O}\right)$$

Efficiency

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

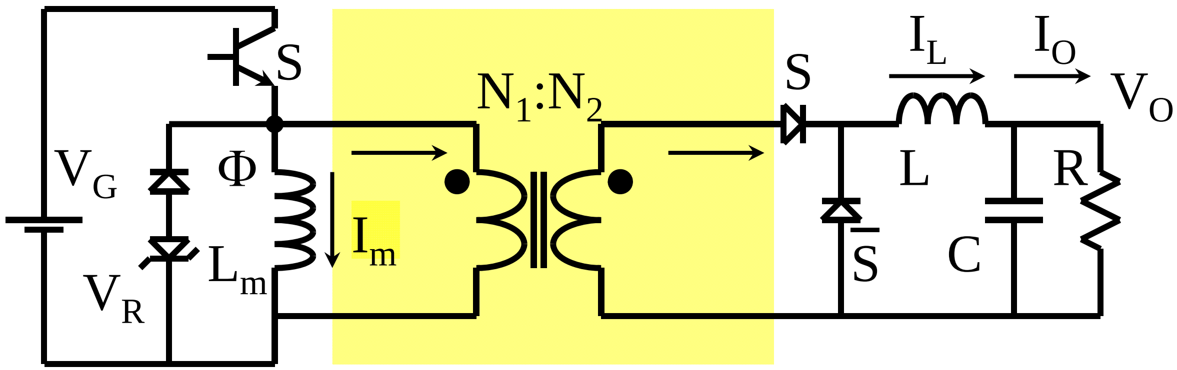


$$\eta = \frac{\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OI}}\right)}{\left(1 + \frac{N_1}{N_2}\frac{V_G D T_S}{2 L_m I_O}\right)}$$

Efficiency

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

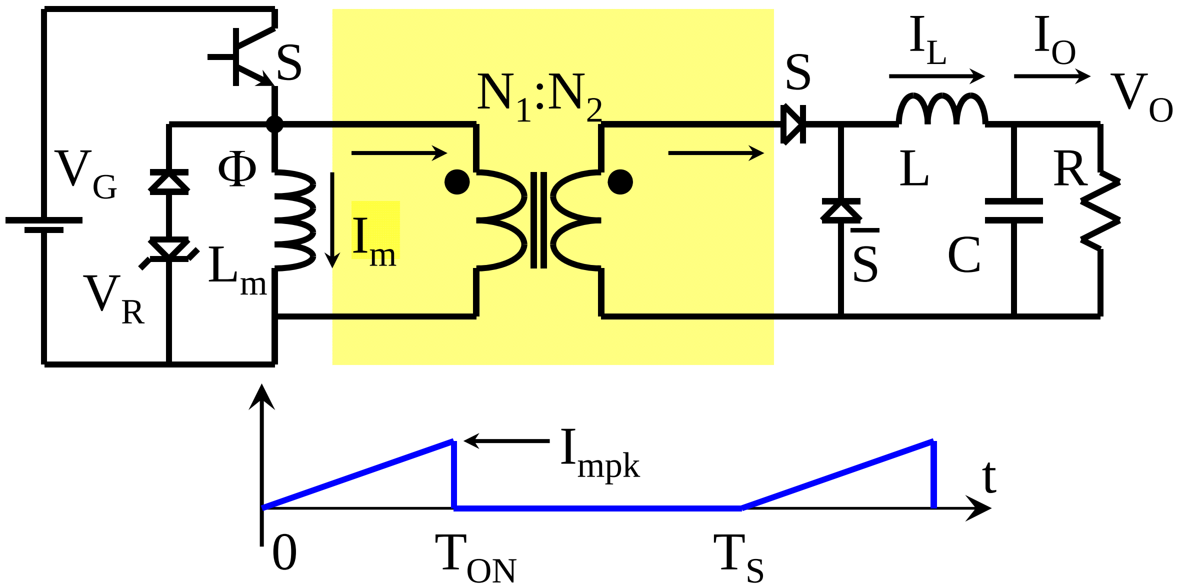


$$\frac{V_O}{V_G} = \frac{N_2}{N_1} D \frac{\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OI}}\right)}{\left(1 + \frac{R_l}{R} + \frac{DR_S}{R} + \frac{DR_P}{R}\frac{N_2^2}{N_1^2}\right)}$$

Parasitic Resistances (R_P, R_S, R_l)

Switched Mode Power Conversion

Forward Converter – Steady State Analysis



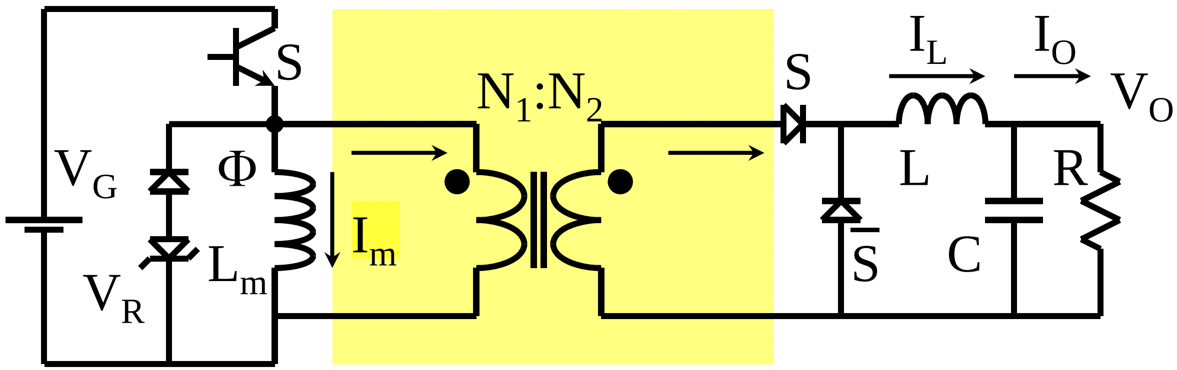
$$P_{Loss} = 0.5 L_m I_{mpk}^2 F_S$$

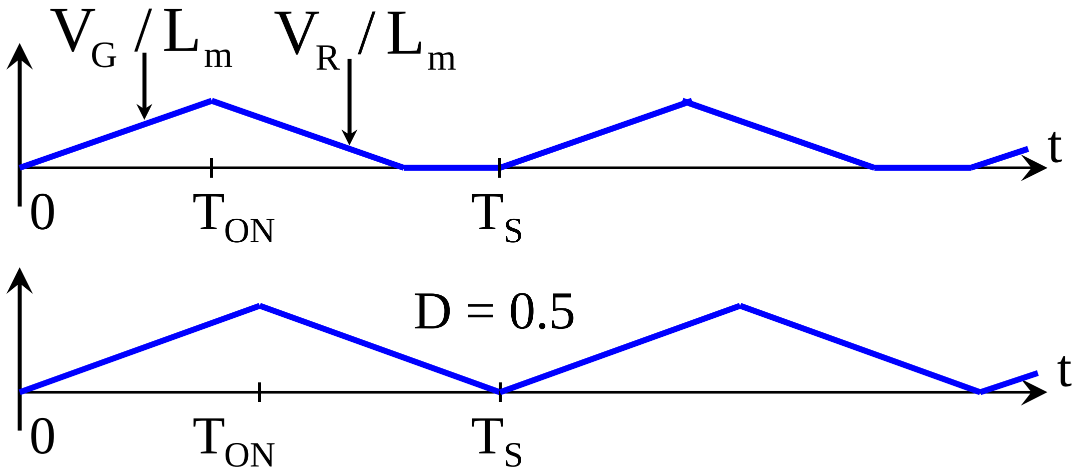
$$P_{Loss} = 0.5 \frac{D^2 V_G^2}{L_m F_S}$$

Power in V_R – Magnetising Energy is Lost in V_R

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

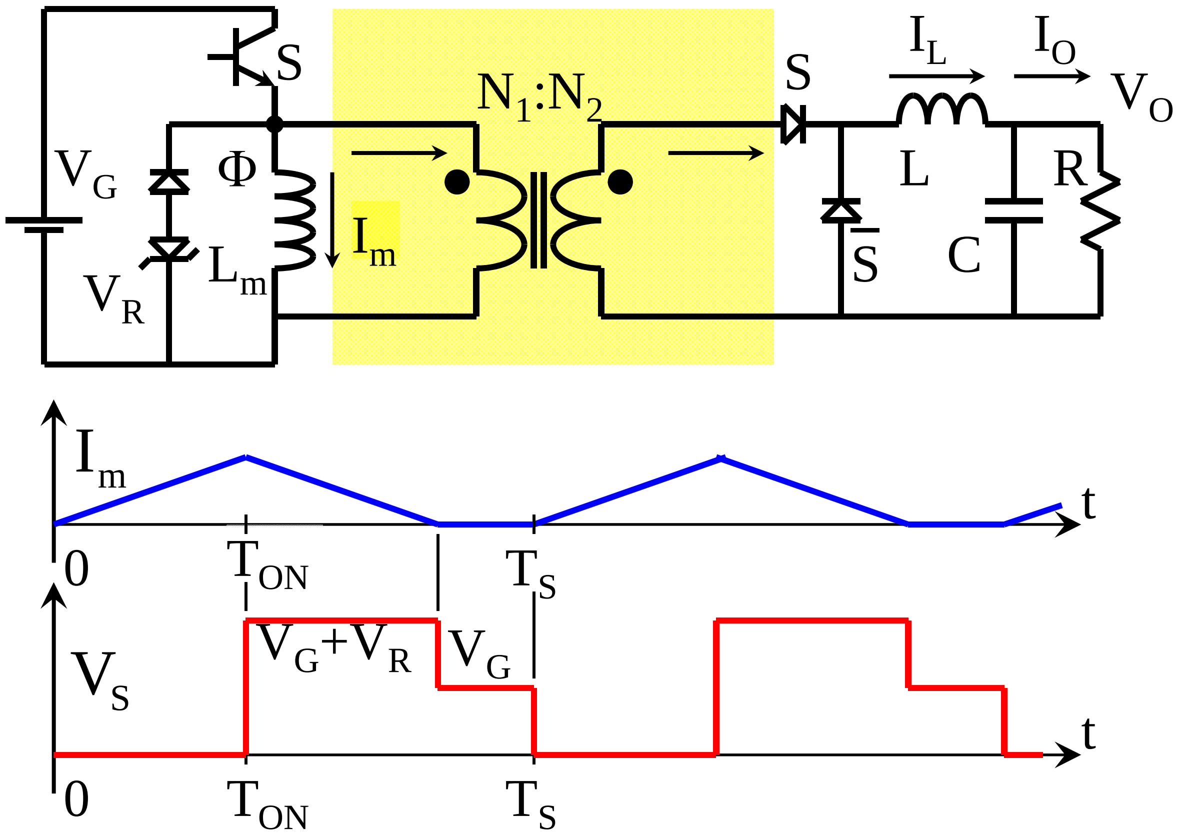




Maximum Duty Ratio of Operation = 0.5 for $V_R = V_G$

Switched Mode Power Conversion

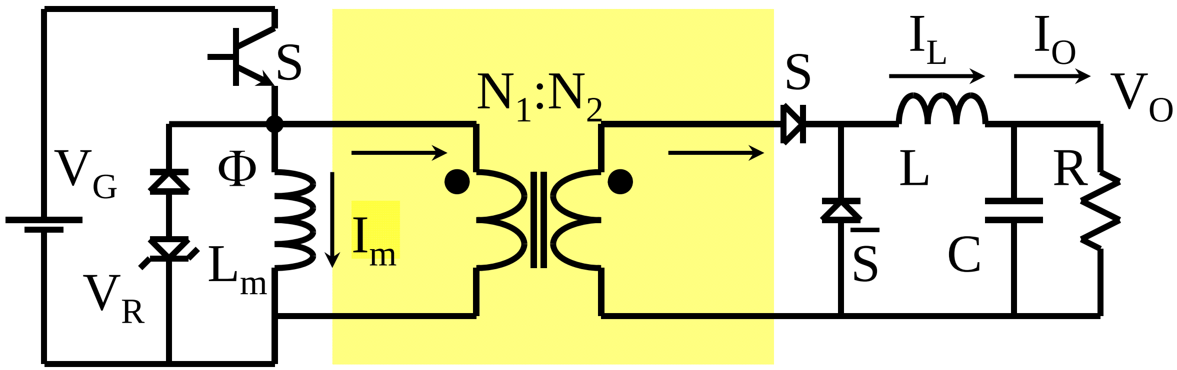
Forward Converter – Steady State Analysis

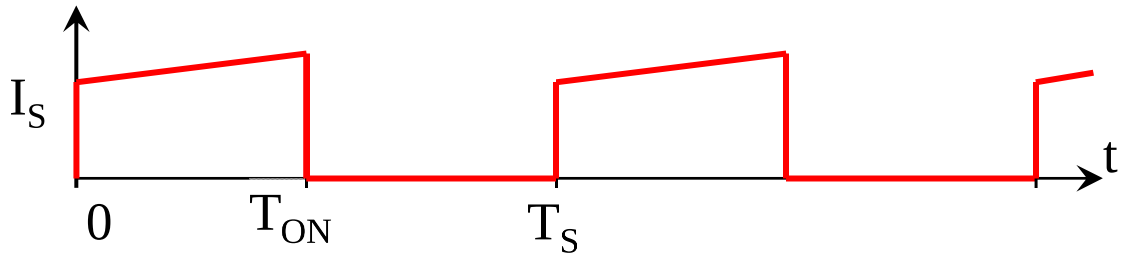


Device (S) Blocking Voltage: $2V_G$ for $V_G = V_R$

Switched Mode Power Conversion

Forward Converter – Steady State Analysis

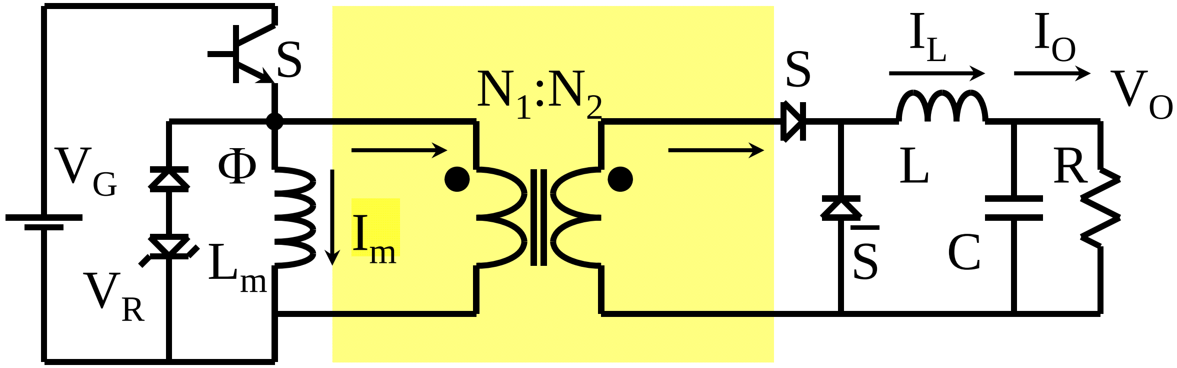




Primary & Secondary Conduction Time:D = 0.5

Switched Mode Power Conversion

Forward Converter – Highlights



Isolation between V_O and V_G

Maximum Duty Ratio: 0.5

Magnetic Core Utilisation: 0.5

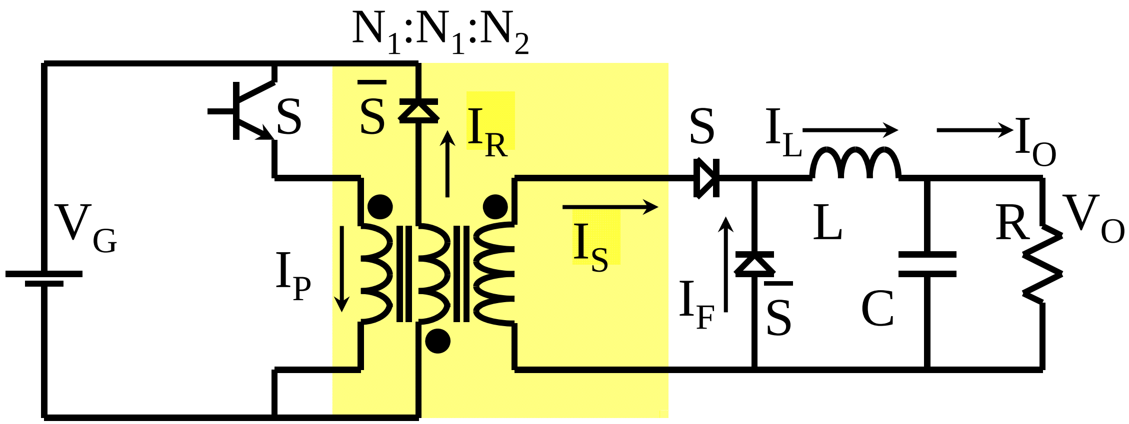
Conductor Utilisation: 0.5

Circuit Voltage: 0.5

Additional Magnetisation Loss

Switched Mode Power Conversion

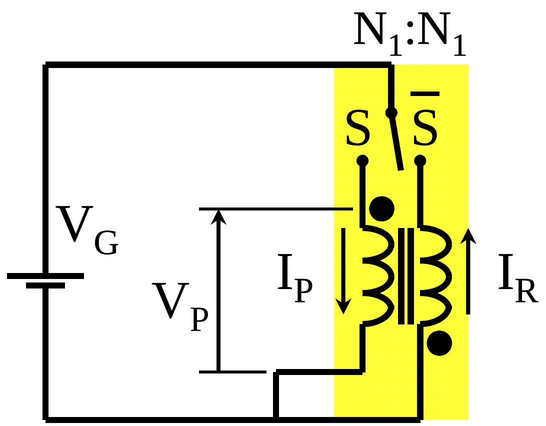
Lossless Forward Converter

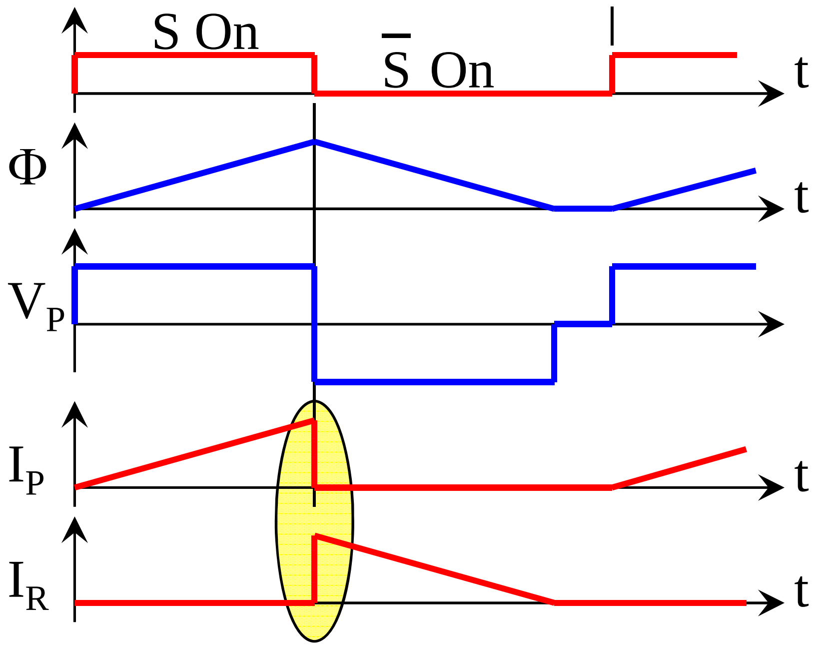


Additional Winding (1:1) Returns the Magnetising Energy to the Source

Switched Mode Power Conversion

Concept Behind Lossless Reset

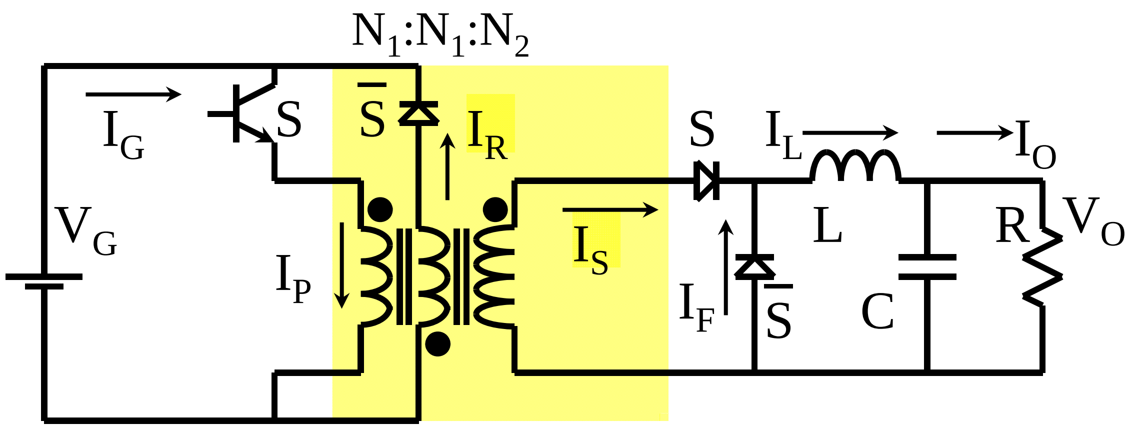




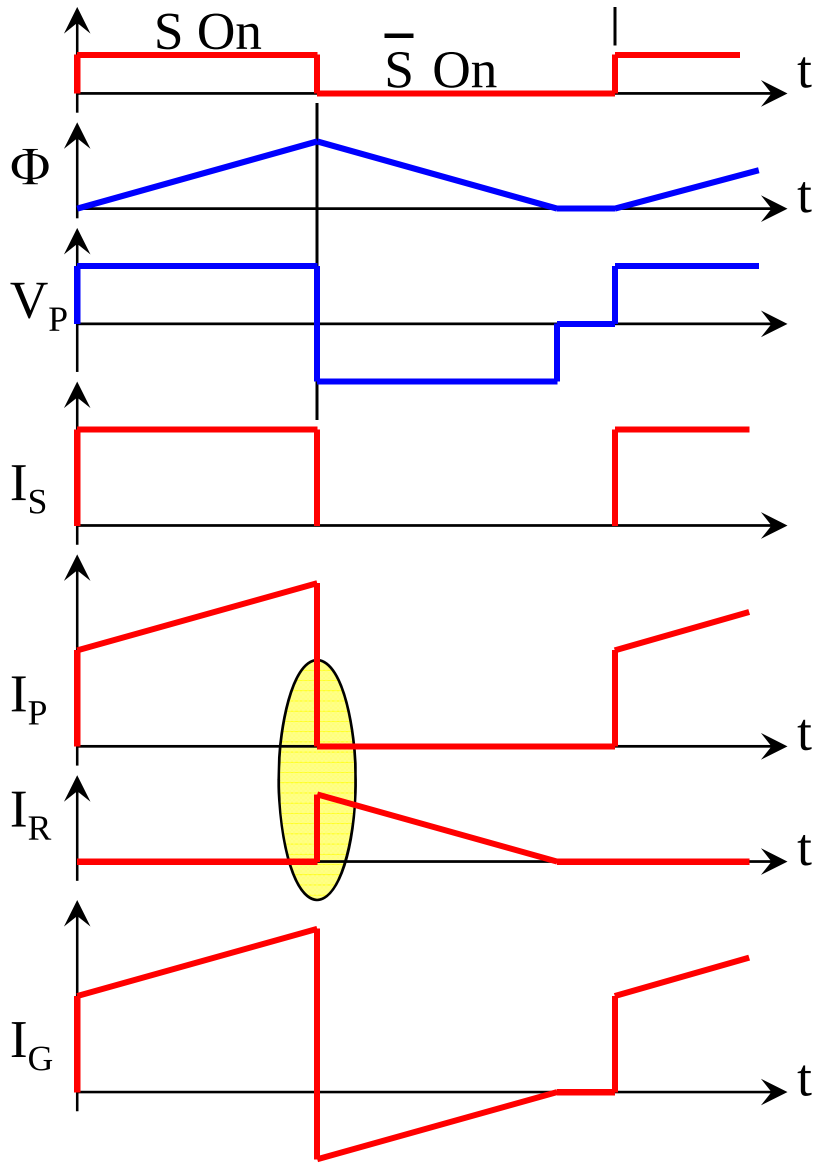
The Reset Winding (1:1) is Tightly Coupled To Primary

Switched Mode Power Conversion

Lossless Forward Converter

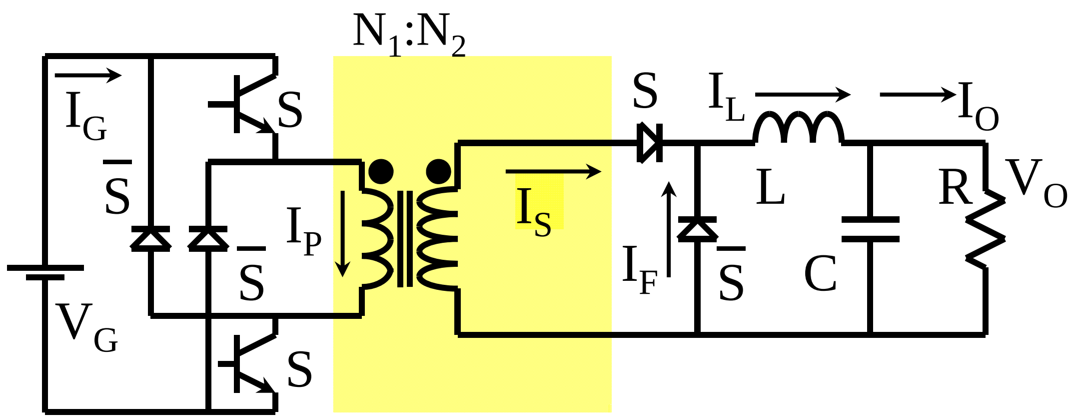


Switched Mode Power Conversion



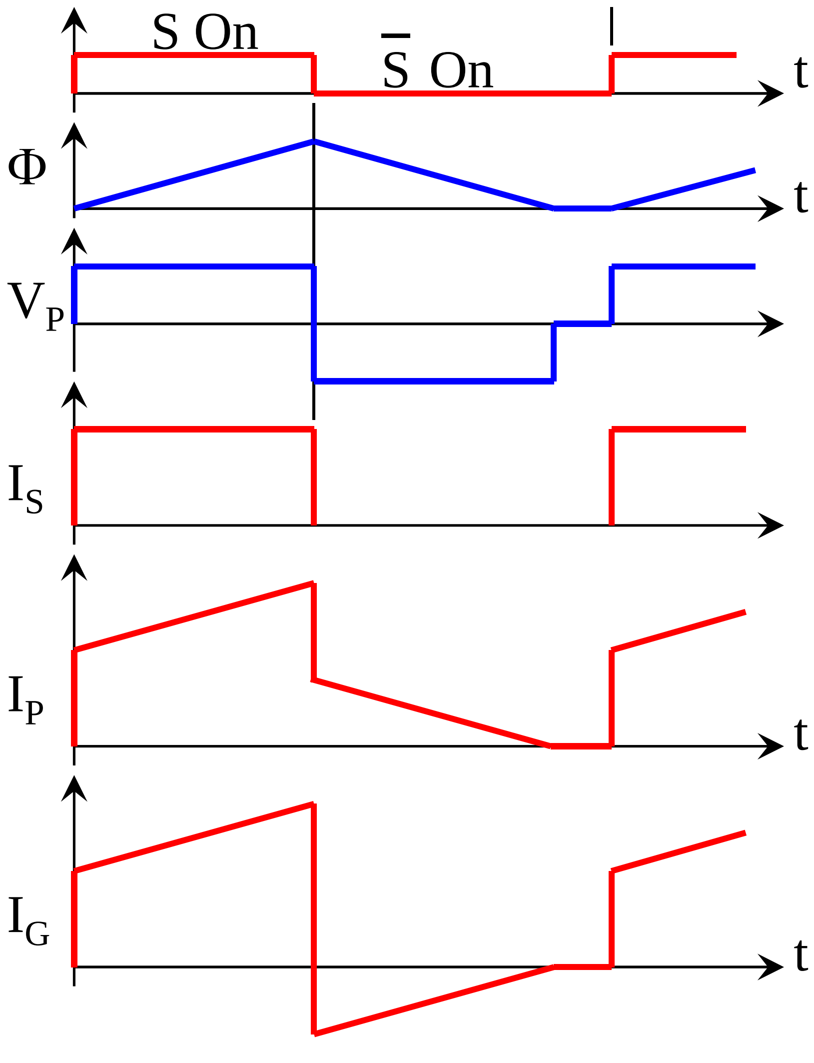
Switched Mode Power Conversion

Lossless Two Switch Forward Converter



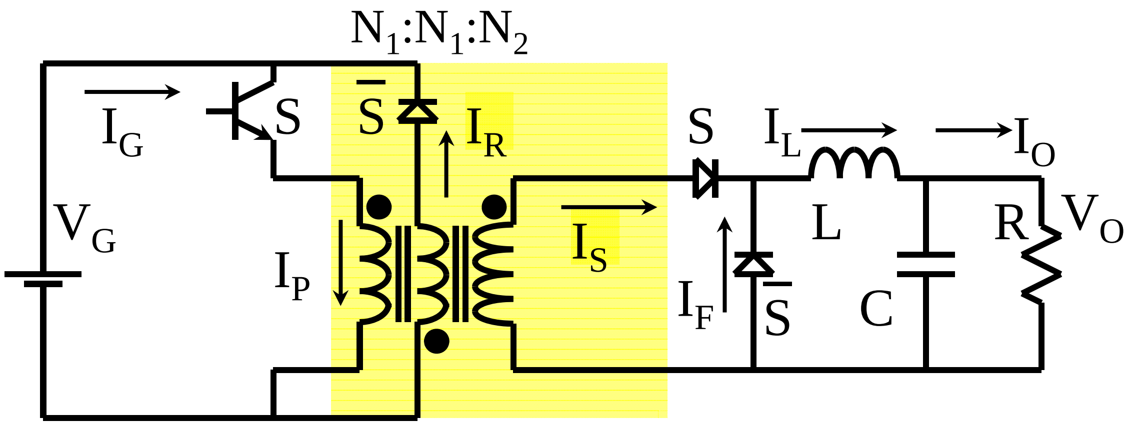
Switched Mode Power Conversion

Lossless Two Switch Forward Converter



Switched Mode Power Conversion

Lossless Reset Forward Converter – Highlights



Isolation between V_O and V_G

Maximum Duty Ratio: 0.5

Magnetic Core Utilisation: 0.5

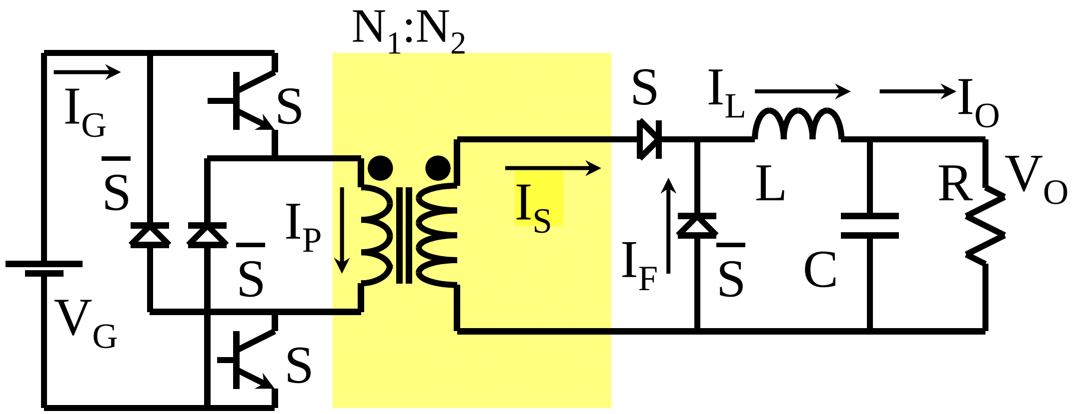
Conductor Utilisation: 0.5

Circuit Voltage: 0.5

Lossless Reset

Switched Mode Power Conversion

Lossless Reset Forward Converter – Highlights



Isolation between V_O and V_G

Maximum Duty Ratio: 0.5

Magnetic Core Utilisation: 0.5

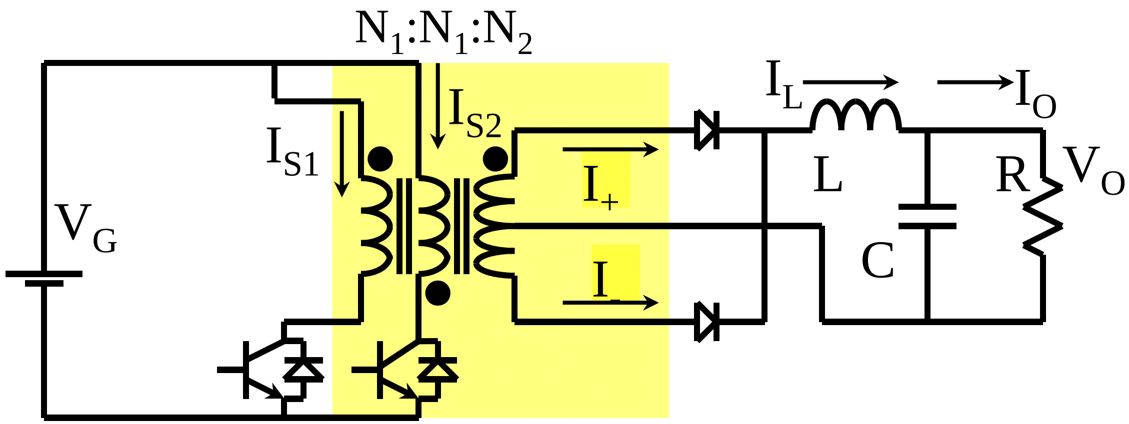
Conductor Utilisation: 0.5

Circuit Voltage: 0.5

Lossless Reset

Switched Mode Power Conversion

Push-Pull Converter



Switches turn-on with PWM in alternate half cycles

Flux resetting is done in Complementary Fashion

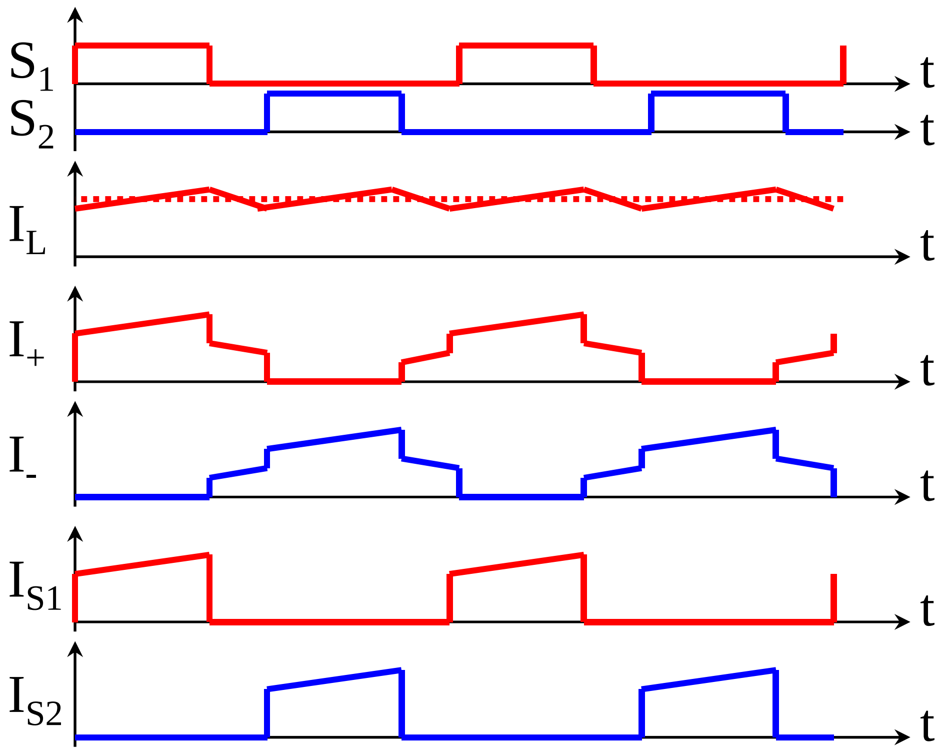
Duty ratio of primary switches < 50%

Secondary duty ratio < 100%

Back-to-Back Forward Converters

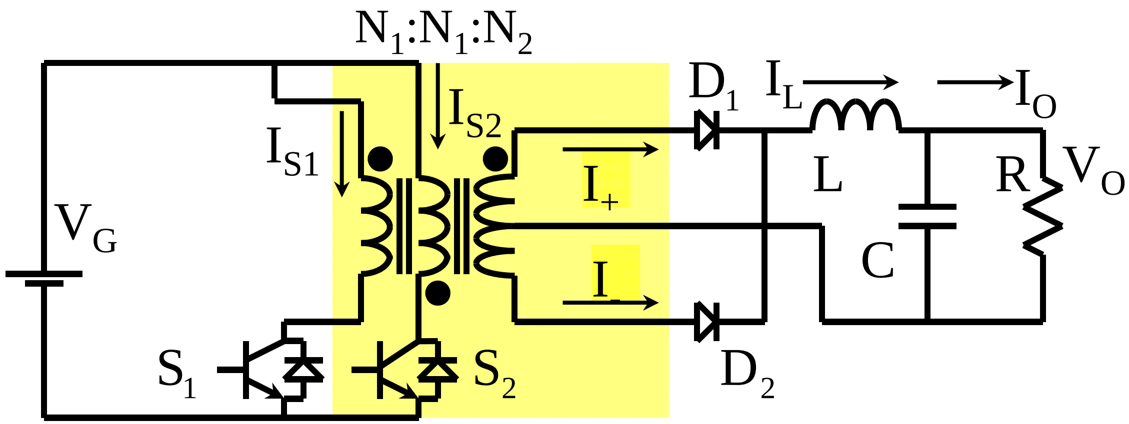
Switched Mode Power Conversion

Push-Pull Converter – Waveforms



Switched Mode Power Conversion

Push-Pull Converter – Highlights



Isolation between V_O and V_G

Maximum Duty Ratio: 1.0

Magnetic Core Utilisation: 1.0

Conductor Utilisation: 0.5

Circuit Voltage: 0.5

Lossless Reset

Switched Mode Power Conversion

Other Isolated Converters

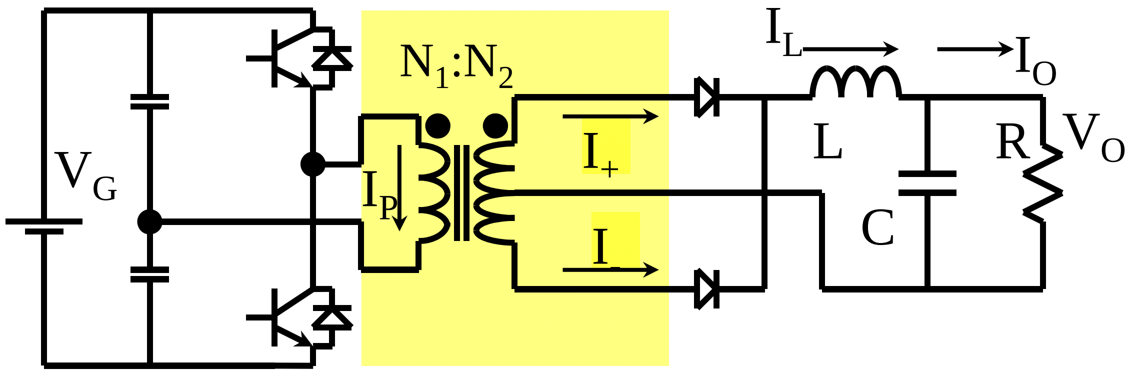
Half Bridge Converter

Full Bridge Converter

Isolated Flyback Converter

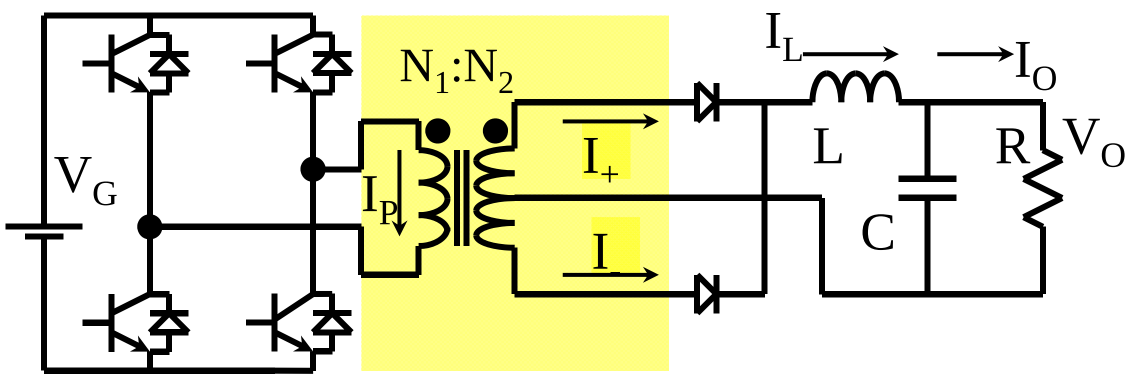
Switched Mode Power Conversion

Half Bridge Converters



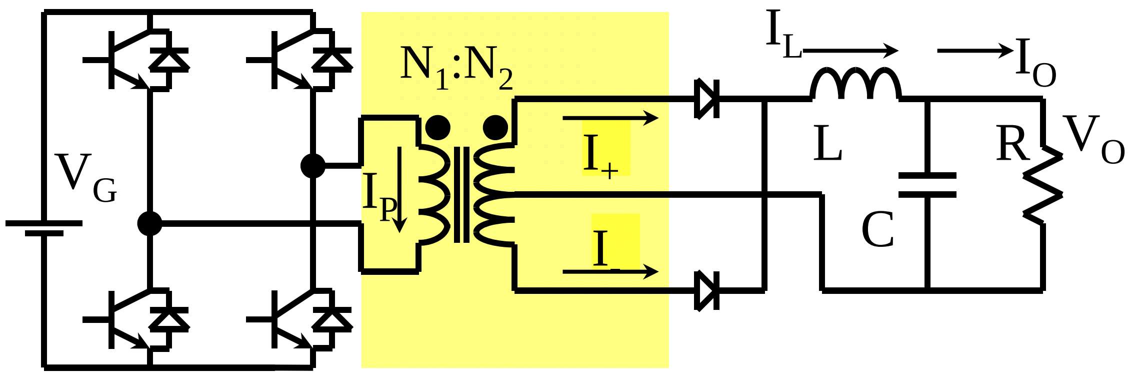
Switched Mode Power Conversion

Full Bridge Converters



Switched Mode Power Conversion

Full Bridge Converters



Isolation between V_O and V_G

Maximum Duty Ratio: 1.0

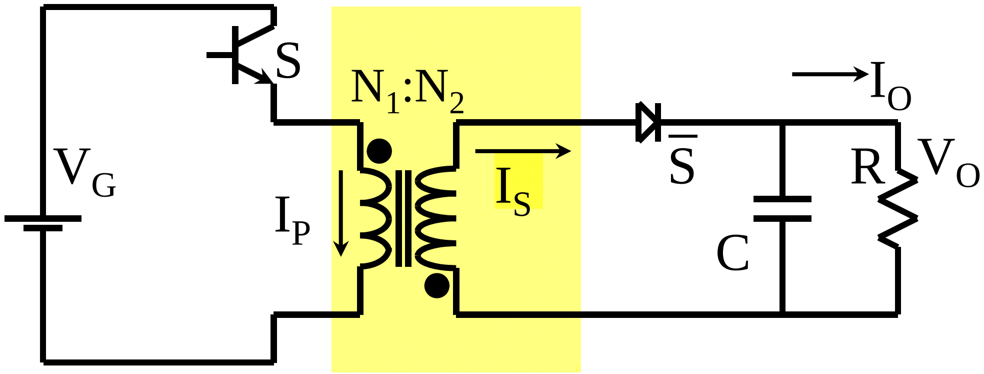
Magnetic Core Utilisation: 1.0

Conductor Utilisation: 1.0

Circuit Voltage: 1.0

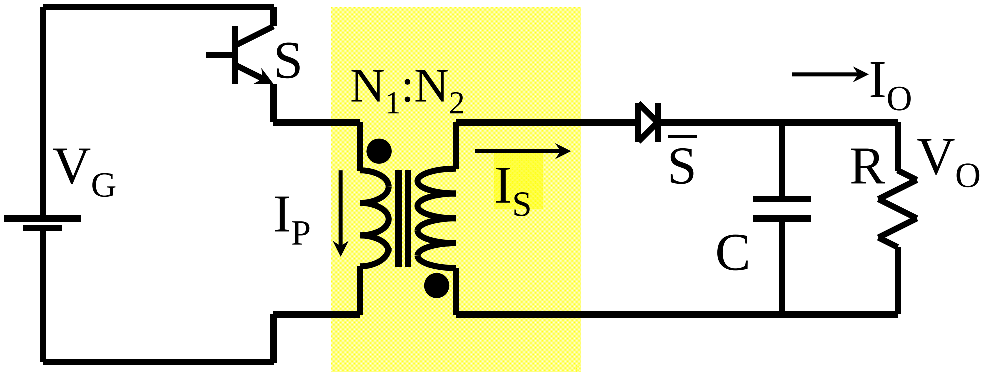
Switched Mode Power Conversion

Isolated Flyback Converters



Switched Mode Power Conversion

Isolated Flyback Converters - Features



Isolation between V_O and V_G

Maximum Duty Ratio: 2/3

Magnetic Core Utilisation: 0.5

Conductor Utilisation: 0.5

Circuit Voltage: 0.5