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

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

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

\( \Phi - V \) Relationship
Switched Mode Power Conversion

Isolated Converters

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

\[ V_1 = N_1 \frac{d\Phi}{dt} \quad \quad V_1 \quad \quad V_2 \quad \quad V_2 = N_2 \frac{d\Phi}{dt} \]

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

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: \( V_1 = V \sin(\omega t) \)
Switched Mode Power Conversion
Isolated Converters

\[ V_1 = N_1 \frac{d\Phi}{dt} \]

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

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

When Average Voltage is Zero, Flux Swing Is Symmetric and Stable
Switched Mode Power Conversion

Isolated Converters

\[ V_1 = N_1 \frac{d\Phi}{dt} \]

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

When Average Voltage is not Zero ..
Switched Mode Power Conversion

Isolated Converters

\[ V_1 = N_1 \frac{d\Phi}{dt} \]

\[ V_1 \]

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

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

Notice the Asymmetric Voltage in Transformer Excitation

\[ T_{\text{ON}} : S \text{ on; } V_1 = V_G \]
\[ T_{\text{OFF}} : \bar{S} \text{ on; } V_1 = 0 \]
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

\[ \Phi \]

\[ T_{\text{ON}} \]

\[ T_{\text{OFF}} \]

\[ \Phi_{\text{max}} \]
Switched Mode Power Conversion

Isolated Converters

Appropriate reset process has to be introduced
Switched Mode Power Conversion

Isolated Converters

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

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

Notice the reset voltage $-V_R$
Switched Mode Power Conversion

Isolated Converters

\[ \frac{V_1}{V_2} = \frac{N_1}{N_2} \]

Magnetising Current (referred to Primary):

\[ \frac{I_2}{I_1} = \frac{N_1}{N_2} \]

Magnetising Ampere – Turns : \((N_1 I_1 - N_2 I_2)\)

Magnetising Current (referred to Primary):

\[ \frac{(N_1 I_1 - N_2 I_2)}{N_1} \]

Magnetising Current
Switched Mode Power Conversion

Isolated Converters

\[ \frac{V_1}{V_2} = \frac{N_1}{N_2} \]

\[ I_2 = \frac{N_1}{N_2} I_1 \]

\[ \Phi = \frac{(N_1 I_1 - N_2 I_2) \mu A_c}{l_c} \]

\( \Phi - I \) Relationships
Switched Mode Power Conversion

Isolated Converters

\[
\frac{V_1}{V_2} = \frac{N_1}{N_2}
\]

\[
I_m = \frac{(N_1 I_1 - N_2 I_2)}{N_1}
\]

\[
L_m I_m = N_1 \Phi = N_1 \left( \frac{(N_1 I_1 - N_2 I_2) \mu A_C}{l_c} \right) = \frac{N_1^2 \mu A_C}{l_c} I_m
\]

\[
L_m = \frac{N_1^2 \mu A_C}{l_c}
\]

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

Ideal Current Ratio – $I_m$ is neglected

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

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

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

\[ I_L = \frac{V_O}{R} \]

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

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

Inductor Ripple Current
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

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

Condition for Low Ripple Current
Switching Period \( T_S \ll \text{Circuit Time Constant (L/R)} \)
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

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

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

Non-Ideality of the Switches
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

\[
\frac{V_O}{V_G} = D \frac{N_2}{N_1} \left( 1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OL}} \right)
\]

Non-Ideality of the Switches
Switched Mode Power Conversion

Forward Converter – Steady State Analysis

Current Conversion Ratio

\[ I_{\text{mpk}} = \frac{V_G D T_S}{L_m} \]
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

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

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

Current Conversion Ratio
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

\[ \frac{V_O}{V_G} = D \frac{N_2}{N_1} \left( 1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OL}} \right) \]

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

Efficiency
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

\[
\eta = \frac{1 - \frac{V_T}{V_G} - \frac{V_D}{V_{ol}}}{1 + \frac{N_1 V_G DT_S}{N_2 2L_m I_O}}
\]

Efficiency
Switched Mode Power Conversion
Forward Converter – Steady State Analysis

Parasitic Resistances (R_P, R_S, R_L)

\[
\frac{V_O}{V_G} = \frac{N_2}{N_1} D \left( 1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OL}} \right) \left( 1 + \frac{R_1}{R} + \frac{D R_S}{R} + \frac{D R_P}{R} \frac{N_2^2}{N_1^2} \right)
\]
Switched Mode Power Conversion

Forward Converter – Steady State Analysis

Power in $V_R$ – Magnetising Energy is Lost in $V_R$

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

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

\[ N_1 : N_1 : N_2 \]

\[ I_G \quad V_G \quad S \quad I_P \quad I_R \quad I_S \quad I_L \quad C \quad R \quad V_O \quad I_O \]
Switched Mode Power Conversion

\[ S_{On}, \bar{S}_{On} \]

\[ \Phi, V_P, I_S, I_P, I_R, I_G \]

\[ t \]
Switched Mode Power Conversion
Lossless Two Switch Forward Converter
Switched Mode Power Conversion
Lossless Two Switch Forward Converter

\[ \Phi(t) \]

\[ V_P(t) \]

\[ I_S(t) \]

\[ I_P(t) \]

\[ I_G(t) \]
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

\[ S_1, S_2, I_L, I_+, I_-, I_{S1}, I_{S2} \]
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

\[ V_G \]
\[ S_1 \]
\[ S_2 \]
\[ N_1:N_1:N_2 \]
\[ I_{S1} \]
\[ I_{S2} \]
\[ I_L \]
\[ I+ \]
\[ I \]
\[ D_1 \]
\[ D_2 \]
\[ L \]
\[ C \]
\[ R \]
\[ V_O \]
Switched Mode Power Conversion

Other Isolated Converters

- Half Bridge Converter
- Full Bridge Converter
- Isolated Flyback Converter
Switched Mode Power Conversion

Half Bridge Converters

![Half Bridge Converter Diagram]

- $V_G$
- $N_1:N_2$
- $I_P$
- $I_I$
- $I_L$
- $I_O$
- $L$
- $R$
- $V_O$
- $C$
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

\[ V_G \quad I_P \quad I_S \quad N_1:N_2 \quad I_O \quad V_O \]
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