Power Stage Designer™ is a Java® based tool that helps engineers speed up their power supply designs as it calculates voltages and currents of 20 topologies according to the user’s inputs. Additionally, Power Stage Designer contains a Bode plotting tool and a helpful toolbox with various functions for power supply design. This document describes how the different features of Power Stage Designer can be used and also explains the calculations behind these functions (for version 4 and higher).

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1 Topologies Window

To start a power supply design with Power Stage Designer, first select a topology from the start screen or the Topology menu. The window changes and displays the schematic of the selected topology with a set of input fields and various output values. After entering the parameters of the power supply specification, Power Stage Designer suggests a value for the output inductance to stay below the entered current ripple requirement. For isolated topologies, the tool also displays a recommendation for the transformer turns ratio (TTR) based on the selected maximum duty cycle and suggests a value for the magnetizing inductance. Users can enter values of their choice and evaluate their impact on voltage and current waveforms and other parameters like on-time, off-time, and duty cycle.

Figure 1 shows the main window of Power Stage Designer displaying supported topologies.

![Figure 1. Main Window of Power Stage Designer Displaying Supported Topologies](image-url)
After clicking on one of the yellow highlighted components in the schematic (see Figure 2), a new window displays the voltage and current waveforms for this specific component (see Figure 3). Additional information like the minimum and maximum voltage, minimum and maximum current, as well as root mean square (RMS), average, and AC values for the current is also provided in this window. The input voltage can be changed across the entire input voltage range with a slider. For most topologies the load current can be altered in the range of 1% to 100% of the entered output current with a second slider. Some topology models do not support such a wide load current range, thus the load current slider can be changed only in the range of 50% and 100%. The Quasi-resonant Flyback model uses a fixed output power as base for all calculations. That is why the load current slider is not available for this specific topology.
NOTE: All equations used for calculations are ideal, with the only exception that the forward voltage of rectifier and freewheeling diodes is considered. For a collection of the equations behind certain topologies, see the Power Topologies Handbook.

2 FET Losses Calculator

The FET Losses Calculator lets the user either compare two different FETs or calculate losses for the main FET and a synchronous rectifier in a hard-switching power stage. Figure 4 shows the FET Losses Calculator window.

NOTE: The Quasi-resonant Flyback, LLC-Half-Bridge, and Phase-Shifted Full-Bridge are resonant topologies. Results might not be accurate.

Figure 4. FET Losses Calculator Window

To attain the most accurate results, it is important to determine the gate drive voltage \( V_{GS} \) of the power management controller as the values for \( Q_{g} \), which is relevant for driver losses, and \( R_{DS(on)} \) are dependent on this voltage and must be obtained from graphs in the data sheet of the FET.

The different losses which can be seen in the FET of a power supply are conducted losses, switching losses, \( C_{oss} \) losses, and body diode losses. Reverse recovery losses are neglected, but can become significant at high switching frequencies.

Conductive losses:

\[
P_{cond} = I_{FET,ms}^2 \times R_{DS(on)}
\]

(1)

Switching losses:

\[
t_{rise} = \frac{(Q_{gs} - Q_{g(th)}) \times R_{g,total}}{V_{GS} - \frac{V_{miller}}{2}} + \frac{Q_{gd} \times R_{g,total}}{V_{GS} - V_{miller}}
\]

\[
t_{fall} = \frac{Q_{gs} \times R_{g,total}}{V_{miller}} + \frac{(Q_{gs} - Q_{g(th)}) \times R_{g,total}}{2 \times \frac{V_{miller}}{2} + \frac{V_{GS(th)}}{2}}
\]

\[
P_{switching} = V_{DS} \times \frac{f_{switch}}{2} \times (t_{rise} \times I_{FET,min} + t_{fall} \times I_{FET,max})
\]

(2)
Coss losses:

\[ P_{\text{Coss}} = C_{\text{OSS}} \times V_{\text{DS}}^2 \times \frac{f_{\text{switch}}}{2} \]  

(3)

Body Diode losses:

\[ P_{\text{body}} = V_{\text{SD}} \times f_{\text{switch}} \times (t_{\text{dead,on}} \times I_{\text{FET,\text{min}}} + t_{\text{dead,off}} \times I_{\text{FET,\text{max}}}) \]  

(4)

The total losses for the main FET can be calculated as indicated in Equation 5

\[ P_{\text{total}} = P_{\text{cond}} + P_{\text{switching}} + P_{\text{Coss}} \]  

(5)

For synchronous rectifiers, the switching losses equal zero due to soft switching, but during the dead time the body diode is conducting. So the total losses result as indicated in Equation 6:

\[ P_{\text{total}} = P_{\text{cond}} + P_{\text{body}} + P_{\text{Coss}} \]  

(6)

Additionally, driver losses occur in the power management controller, which can be calculated as shown in Equation 7:

\[ P_{\text{driver}} = Q_g \times V_{\text{GS}} \times f_{\text{switch}} \]  

(7)

Power management controllers typically have a limited amount of gate drive current they can source and sink. Therefore, it is important to adjust the total resistance in the gate drive path so the resulting gate drive current is equal to or smaller than the limit in the data sheet.

3 Capacitor Current Sharing Calculator

When connecting different kinds of capacitors in parallel at the input or output of a power supply, the RMS current going through each capacitor is different as it depends on the impedance of the capacitors across the entire frequency range. For exact results for the RMS current per capacitor, impedances and currents must be calculated for all harmonics of the switching frequency. The RMS current for each harmonic must be derived with a Fast Fourier Transformation (FFT) of the total current signal based on the ratio between total impedance and single-capacitor impedance at that harmonic frequency. The total RMS current per capacitor can then be calculated with the quadratic mean of all harmonic RMS current values for this capacitor.

Figure 5 shows the Capacitor Current Sharing Calculator.

**NOTE:** In Power Stage Designer, the impedances and the RMS currents are only calculated at the switching frequency. Thus, the resulting RMS currents are rough estimations.
The impedance for one capacitor at the switching frequency (n can be 1, 2, or 3 and refers to the capacitor index) can be calculated as indicated in Equation 8:

\[
Z_{\text{cap,n}} = \sqrt{\frac{ESR C_n^2}{2 \times \pi \times f_{\text{switch}} \times C_n} - \frac{1}{2 \times \pi \times f_{\text{switch}} \times ESL C_n}}
\]  

(8)

Typical ESL values for capacitors are from 1 nH to 7 nH. By assuming 6nH/cm as parasitic inductance for a conductor, the inductance for a ceramic capacitor can be estimated by multiplying this value with the capacitor length. PCB traces and vias can increase this value slightly (see [1]).

The total impedance of three parallel capacitors at the switching frequency results as seen in Equation 9:

\[
Z_{\text{total}} = \frac{1}{\frac{1}{Z_{\text{cap,1}}} + \frac{1}{Z_{\text{cap,2}}} + \frac{1}{Z_{\text{cap,3}}}}
\]  

(9)

The RMS current of one capacitor, while neglecting all other harmonics besides the switching frequency, can be calculated as seen in Equation 10:

\[
I_{\text{rms,\text{cap,n}}} = I_{\text{rms,\text{total}}} \times \frac{Z_{\text{total}}}{Z_{\text{cap,n}}}
\]  

(10)
AC/DC power supplies typically require a bulk capacitor behind the input rectifier that provides a quasi-constant input voltage for the converter stage (see Figure 6). Power Stage Designer can calculate the minimum capacitance based on the desired minimum bulk voltage $V_{\text{bulk,min}}$, the maximum acceptable voltage ripple $\Delta V$ in percent, the input power $P_{\text{in}}$ and the minimum line frequency $f_{\text{line,min}}$ (see Equation 11).

$$V_{\text{AC,min}} = \frac{V_{\text{bulk,min}}}{(1 - \Delta V) \times \sqrt{2}}$$

$$t_{\text{discharge}} = \frac{1}{4 \times f_{\text{line,min}}} + \frac{1}{2 \times \pi \times f_{\text{line,min}}} \times \sin^{-1}(1 - \Delta V)$$

$$t_{\text{charge}} = \frac{1}{4 \times f_{\text{line,min}}} - \frac{1}{2 \times \pi \times f_{\text{line,min}}} \times \sin^{-1}(1 - \Delta V)$$

$$C_{\text{bulk}} = \frac{2 \times P_{\text{in}} \times t_{\text{discharge}}}{V_{\text{bulk,min}}^2 \times \left( \frac{1}{1 - \Delta V} \right)^2 - 1}$$

$$I_{\text{bulk,rms}} = \sqrt{\left( \frac{C_{\text{bulk}} \times V_{\text{bulk,min}} \times \left( \frac{1}{1 - \Delta V} - 1 \right)}{t_{\text{charge}} \times \sqrt{3}} \right)^2 + \left( \frac{P_{\text{in}}}{V_{\text{bulk,min}}} \right)^2}$$

(11)
5 RCD-Snubber Calculator for Flyback Converters

In Flyback converters the output voltage is reflected from the secondary to the primary side. Additionally, parasitics caused by the layout and the Flyback transformer leakage inductance can cause a voltage spike followed by ringing when the MOSFET is turning off. The voltage spike and the ringing can be limited by implementing an RCD-snubber circuit in parallel to the primary winding. The energy of the high-frequency ringing is dissipated in the RCD-network. The RCD-Snubber Calculator for Flyback converters in Power Stage Designer helps the designer choose the starting values for snubber resistor and capacitor based on the user’s inputs, which follow:

- Sum of output voltage and rectifier voltage
- Flyback transformer turns ratio
- Leakage inductance
- Maximum primary current
- Switching frequency
- Permitted voltage overshoot as a factor
- Snubber capacitor voltage ripple in percent

Figure 7 shows the RCD-Snubber Calculator for Flyback Converters window.

\[ V_{\text{snub}} = K_{\text{snub}} \times \frac{N_p}{N_s} \times \left( V_{\text{out}} + V_f \right) \]  

(12)
Starting Snubber resistance:

\[ R_{\text{snub}} = \frac{1}{2} \times L_{\text{leak}} \times I_{\text{max, pri}}^2 \times \frac{V_{\text{snub}}^2}{V_{\text{snub}} - \frac{N_p}{N_s} \times (V_{\text{out}} + V_f)} \times f_{\text{switch}} \]

Starting Snubber capacitance:

\[ C_{\text{snub}} = \frac{V_{\text{snub}}}{\Delta V_{\text{snub}} \times R_{\text{snub}} \times f_{\text{switch}}} \]

6 RC-Snubber Calculator

An RC-Snubber circuit is one option to reduce ringing in a switch mode power supply. Alternatives are the use of MOSFET gate resistors or a resistor in series with the bootstrap capacitor to slow down rise and/or fall times. With the RC-Snubber Calculator, Power Stage Designer helps the designer determine starting values for the snubber resistor and capacitor.

Figure 8 shows the RC-Snubber Calculator window.

- Measure the oscillation frequency \( f_0 \) of the circuit without a snubber network.
- Add a capacitor \( C_1 \) in parallel with the rectifier or FET and measure the shifted oscillation frequency \( f_1 \). Select a \( C_1 \) value that is several times larger than the stated typical capacitance of the rectifier at full reverse voltage or the output capacitance of the FET.
- After entering these three values, the tool will propose starting values for the R-C Snubber network.
Frequency shift ratio:
\[ m = \frac{f_0}{f_1} \]  
(15)

Parasitic capacitance:
\[ C_0 = \frac{C_1}{m^2 - 1} \]  
(16)

Parasitic inductance:
\[ L = \frac{m^2 - 1}{(2 \times \pi \times f_0)^2 \times C_1} \]  
(17)

Starting Snubber capacitance:
\[ C_{\text{snub}} = 3 \times C_0 \]  
(18)

Starting Snubber resistance:
\[ R_{\text{snub}} = \sqrt{\frac{L}{C_0}} \]  
(19)

7 Output Voltage Resistor Divider

The Output Voltage Resistor Divider Tool calculates the closest resistor values of the chosen E-Series to match the specified output voltage based on the entered reference voltage, reference voltage tolerance, and desired resistance value. The resistance value can be entered for the high-side (HS) or the low-side (LS) resistor. It is also possible to parallel two resistors to get more precise results. The following equations calculate the resulting output voltage while respecting resistor tolerances and reference voltage tolerances. However, because effects caused by the bias current are not considered for the calculations, these values are estimates.

Figure 9 shows the Output Voltage Resistor Divider Calculator window.
Effective output voltage with chosen resistance values (see Equation 20):

\[ V_{\text{out,real}} = V_{\text{ref}} \times \frac{R_{\text{HS}} + R_{\text{LS}}}{R_{\text{LS}}} \]

\[ \Delta V_{\text{OUT}} = \frac{V_{\text{out,real}} - V_{\text{out}}}{V_{\text{out}}} \]  

(20)

Bias current:

\[ I_{\text{bias}} = \frac{V_{\text{out,real}}}{R_{\text{HS}} + R_{\text{LS}}} \]  

(21)

Worst-case minimum output voltage:

\[ V_{\text{out,min}} = V_{\text{ref,min}} \times \frac{R_{\text{HS,min}} + R_{\text{LS,max}}}{R_{\text{LS,max}}} \]

\[ \Delta V_{\text{OUT,min}} = \frac{V_{\text{out,min}} - V_{\text{out}}}{V_{\text{out}}} \]  

(22)

Worst-case maximum output voltage:

\[ V_{\text{out,max}} = V_{\text{ref,max}} \times \frac{R_{\text{HS,max}} + R_{\text{LS,min}}}{R_{\text{LS,min}}} \]

\[ \Delta V_{\text{out,max}} = \frac{V_{\text{out,max}} - V_{\text{out}}}{V_{\text{out}}} \]  

(23)

8 Dynamic Analog Output Voltage Scaling

If the output voltage of a power supply must be adjustable, add a third resistor to the feedback resistor divider and apply an analog voltage to this resistor (for example, with the DAC of a microcontroller). The analog signal can also be provided by smoothing a PWM signal with a low-pass filter. After entering the minimum output voltage, maximum output voltage, reference voltage, maximum adjusting voltage signal, and the desired value for the top feedback resistor, Power Stage Designer calculates the required bottom feedback resistance and the adjusting voltage signal series resistance, as well as the minimum bias current going through the top feedback resistor.

Figure 10 shows the Dynamic Analog Output Voltage Scaling Calculator window.
Dynamic Digital Output Voltage Scaling

Dynamic output voltage adjustment can also be achieved by applying GPIO signals to an array of resistors and signal FET combinations in parallel with the low-side resistor of the feedback divider. For most cases, a microcontroller output in open-drain configuration can be used instead of an external signal FET because it is already part of the system. Power Stage Designer calculates the low-side feedback resistor, the voltage per step, the bias current, and the series resistance for each bit based on the output voltage range, the reference voltage, the number of bits, and the value of the high-side feedback resistor.

Figure 11 shows the Dynamic Digital Output Voltage Scaling Calculator window.

\[
I_{R1,\text{min}} = \frac{V_{\text{out,min}} - V_{\text{ref}}}{R_1}
\]
\[
R_3 = \frac{R_1 \times V_{\text{adj,max}}}{V_{\text{out,max}} - V_{\text{ref}} - R_1 \times I_{R1,\text{min}}}
\]
\[
R_2 = \frac{R_1 \times R_3 \times V_{\text{ref}}}{R_3 \times V_{\text{out,max}} - R_3 \times V_{\text{ref}} - R_1 \times V_{\text{ref}}}
\]

9 Dynamic Digital Output Voltage Scaling

Figure 10. Dynamic Analog Output Voltage Scaling Calculator Window
Figure 11. Dynamic Digital Output Voltage Scaling Calculator Window

\[
I_{R1,\text{min}} = \frac{V_{\text{out},\text{min}} - V_{\text{ref}}}{R_1} 
\]

\[
R_2 = \frac{R_1 \times V_{\text{ref}}}{V_{\text{out},\text{min}} - V_{\text{ref}}} 
\]

\[
V_{\text{step}} = \frac{V_{\text{out,max}} - V_{\text{out,min}}}{2^{\text{Bits}} - 1} 
\]

\[
R_{\text{Bitn}} = \frac{1}{\frac{V_{\text{out},\text{min}} + 2^{\text{Bit}} \times V_{\text{step}} - V_{\text{ref}}}{R_1 \times V_{\text{ref}}} - 1} 
\]

The LM10011 is a device that has this feature integrated for 4/6-Bit VID.
10 Unit Converter

The Unit Converter can help power supply designers convert typical parameters related to power supplies. These parameters are magnetic flux, gain, length, weight, airstream, PCB copper thickness, and temperature. Figure 12 shows the Unit Converter window.

![Unit Converter Window](image)

Figure 12. Unit Converter Window

11 Loop Calculator

The Loop Calculator can help power supply designers with the compensation network for voltage mode controlled (VMC) buck converters or current mode controlled (CMC) buck, boost, inverting buck-boost, forward, and flyback converters operating in continuous conduction mode (CCM). The transfer functions have been simplified, thus the results give a first-order approximation of how the Bode plot of the power supply will appear. Figure 13 shows the Loop Calculator window.
The following steps apply when using the Loop Calculator.

1. Select the topology/control scheme and the type of compensation for the design with the radio buttons in the bottom-left corner. Typically, only the VMC buck needs a Type III Compensation. For all CMC topologies, a Type II Compensation is usually sufficient.

2. Fill in all input fields with white background. If the Loop Calculator is started from one of the supported topologies, applicable values from the topologies window will directly transfer to the Loop Calculator window.

3. Under General Information (from the schematic) sum the capacitance of the same output capacitor types and calculate their effective ESR. The DC-biasing effect for ceramic capacitors must be considered because it can have a major impact on the accuracy of the gain and phase plot of the power stage.

4. Enter the Gain Information (from the schematic and the data sheet for the controller).

5. Fill in the values for RFBT and RFBB. With this information the Loop Calculator can suggest values for the compensation network of the entered power supply design.
The compensation network suggestions are calculated as follows:

**CAUTION**
If unusual input conditions are applied, the suggestions of the tool do not necessarily lead to a stable system.

- Compensation zeroes are placed on the pole of the transfer function of the power stage \( (L \text{ and } C_{\text{out}} \text{ double pole for VMC, } R_{\text{out}} \text{ and } C_{\text{out}} \text{ single pole for CMC}) \).
- Compensation poles are placed on the lower of either half of the switching frequency or the ESR zero for Buck derived topologies.
- Compensation poles are placed on the lower of either the right half plane zero (RHPZ) frequency or the ESR zero frequency for Boost/Buck-Boost derived topologies.
- The maximum achievable crossover frequency is approximately two decades below the GBWP (gain bandwidth product) of the error amplifier. The gain of the compensation network should never go above the open loop gain of the error amplifier. Otherwise, the error amplifier will be clipping.
- For Boost/Buck-Boost derived topologies the desired crossover frequency is automatically set to 1/5 of the RHPZ frequency.

### 11.1 Inputs

Table 1 lists general information:

**Table 1. General Information**

| \( V_{\text{in}} \) | Input voltage |
| \( V_{\text{out}} \) | Output voltage |
| \( I_{\text{out}} \) | Load current |
| \( L \) | Inductance / Flyback primary inductance |
| \( DCR_L \) | Inductor DC resistance |

| \( C_{\text{out},1} \) | Capacitance output capacitor 1 |
| \( \text{ESR}_{\text{out},1} \) | Equivalent series resistance output capacitor 1 |
| \( C_{\text{out},2} \) | Capacitance output capacitor 2 |
| \( \text{ESR}_{\text{out},2} \) | Equivalent series resistance output capacitor 2 |
| \( f_{\text{switch}} \) | Switching frequency |
| \( N_p/N_s \) | Transformer turns ratio |
| \( \text{Opto BW} \) | Optocoupler bandwidth |

Table 2 lists gain information:

**Table 2. Gain Information**

| \( V_{\text{ramp}} \) | PWM ramp voltage |
| \( G_m \) | Error amplifier transconductance |
| \( A_s \) | Current-sense amplifier gain |
| \( R_s \) | Current-sense resistance |
| \( A_{\text{OL}} \) | Error amplifier open-loop gain |
| \( \text{GBWP} \) | Error amplifier gain bandwidth product |
| \( R_p/R_o \) | Optocoupler transfer ratio |
| \( V_{\text{slope}} \) | Slope compensation voltage |
| \( \text{SLM} \) | Slope compensation multiplier |
Current-sense gain $A_s$ and current-sense resistance $R_s$:

For converters with integrated current-sensing circuits, sometimes there are no specific values for $A_s$ and $R_s$ in the data sheet. Instead, a value for $G_{m,ps}$ (can also appear as “COMP to switch current transconductance”) is typically displayed. Equation 26 shows the relationship between these values.

$$G_{m,ps} = \frac{1}{A_s \times R_s}$$

(26)

In this case, values for $A_s$ and $R_s$ must be chosen to have the stated $G_{m,ps}$ as a result. (For example, use the $R_{DS(on)}$ of the internal FET for $R_s$ and calculate $A_s$ from Equation 26.)

The input field for $V_{\text{slope}}$ offers the user the option to use either $V_{\text{slope}}$ or a slope compensation multiplier (SLM), in case the value for $V_{\text{slope}}$ cannot be calculated by the designer (for example, because of internal slope compensation). Switching between these two variables can be done by right-clicking on the $V_{\text{slope}}$/SLM input field.

$V_{\text{slope}}$:
- Calculate the value for $V_{\text{slope}}$ with the equations from the data sheet. If the device has internal slope compensation, a value for $V_{\text{slope}}$ is typically given in the Electrical Characteristics section.

SLM:
- SLM is a variable to simulate the slope compensation under certain circumstances. How it affects calculations can be found in the subsections for each topology.
- Ideal slope compensation will be calculated with a value of 1.
- Values greater than 1 show how the converter will drift to VMC with increasing values of SLM, as the information of the original current signal will be lost at a certain point. A Type III compensation network would then be necessary to compensate the converter.
- Values in the range from 0 to 1 simulate conditions when not enough slope compensation is present, and a resonance will become visible at half the switching frequency caused by the quality factor of the double pole of the inductance.

Table 3 lists component values:

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{FBT}$</td>
<td>Top feedback resistance</td>
</tr>
<tr>
<td>$R_{FBB}$</td>
<td>Bottom feedback resistance</td>
</tr>
<tr>
<td>$R_F$</td>
<td>Compensation feed-forward resistance</td>
</tr>
<tr>
<td>$R_{COMP}$</td>
<td>Compensation resistance</td>
</tr>
<tr>
<td>$C_F$</td>
<td>Compensation feed-forward capacitance</td>
</tr>
<tr>
<td>$C_{COMP}$</td>
<td>Compensation capacitance</td>
</tr>
<tr>
<td>$C_{HF}$</td>
<td>Compensation high-frequency capacitance</td>
</tr>
</tbody>
</table>

For Type II and Type III transconductance compensation networks, the Loop Calculator offers an option to use an additional Feed-Forward Capacitor in parallel with $R_{FBT}$. This option can be enabled by right-clicking on the $C_F$ input field and choosing Use.

At start-up the Loop Calculator displays only the resulting Bode plot for the Total Gain and Total Phase. The graphs for the Gain of the Power Stage, Phase of the Power Stage, Gain of the Error Amplifier, Phase of the Error Amplifier and the Error Amplifier Open Loop Gain can be switched on by selecting the respective checkbox.
11.2 Transfer Functions

11.2.1 Output Capacitor Transfer Function

For two parallel capacitors the transfer function can be written as shown in Equation 27:

\[
E(s) = \frac{1 + \frac{s}{\omega_{Z1}}}{1 + \frac{s}{\omega_{P1}}} \times \frac{1 + \frac{s}{\omega_{Z2}}}{1 + \frac{s}{\omega_{P2}}}
\]

(27)

There are two ESR zeros:

\[
\omega_{Z1} = \frac{1}{\text{ESR}_{\text{out,1}} \times C_{\text{out1}}}
\]

\[
\omega_{Z2} = \frac{1}{\text{ESR}_{\text{out,2}} \times C_{\text{out2}}}
\]

(28)

And there are two ESR poles:

\[
\omega_{P1} = \frac{\left(C_{\text{out1}} + C_{\text{out2}}\right)}{\text{ESR}_{\text{out,1}} \times C_{\text{out1}} \times C_{\text{out2}}}
\]

\[
\omega_{P2} = \frac{\left(C_{\text{out1}} + C_{\text{out2}}\right)}{\text{ESR}_{\text{out,2}} \times C_{\text{out1}} \times C_{\text{out2}}}
\]

(29)

11.2.2 Transfer Function VMC Buck Power Stage

\[
\frac{\dot{v}_{\text{out}}}{\dot{v}_c} = A_{\text{VC}} \times \frac{E(s)}{1 + \frac{s}{Q_0 \times \omega_0} + \frac{s^2}{\omega_0^2}}
\]

(30)

DC-Gain:

\[
A_{\text{VC}} = \frac{V_{\text{in}}}{V_{\text{ramp}}}
\]

(31)

LC double pole:

\[
\omega_0 = \frac{1}{\sqrt{L \times C_{\text{out}}}}
\]

(32)

Calculate Q0 with the larger of the ESR values:

\[
Q_0 = \frac{\frac{\omega_0}{\text{DCR}_{\text{L}}}}{L} + \frac{1}{C_{\text{out}} \times \left(\frac{V_{\text{out}}}{I_{\text{out}}} + \text{ESR}_{\text{out,n}}\right)}
\]

(33)
11.2.3 Transfer Function CMC Buck Power Stage

\[ \frac{\dot{v}_{out}}{\dot{v}_c} = A_{VC} \times \frac{E(s)}{\left(1 + \frac{s}{\omega_p}\right) \times \left(1 + \frac{s}{Q_L \times \omega_L} + \frac{s^2}{\omega_L^2}\right)} \]  

\[ D = \frac{V_{out}}{V_{in}} \]  

DC-Gain:

\[ A_{VC} = \frac{R_{out}}{A_s \times R_s} \]  

Load pole:

\[ \omega_p = \frac{1}{C_{out} \times R_{out}} \]  

\[ \omega_L = \pi \times f_{\text{switch}} \]  

With \( V_{\text{slope}} \):

\[ s_e = V_{\text{slope}} \times f_{\text{switch}} \]  

With SLM:

\[ s_e = \frac{\text{SLM} \times V_{out} \times A_s \times R_s}{L} \]  

\[ s_n = \frac{(V_{in} - V_{out}) \times A_s \times R_s}{L} \]  

\[ Q_L = \frac{1}{\pi \times \left[1 + \frac{s_e}{s_n} \right] \times (1 - D) - 0.5} \]  

11.2.4 Transfer Function CMC Boost Power Stage

\[ \frac{\dot{v}_{out}}{\dot{v}_c} = A_{VC} \times \frac{\left(1 - \frac{s}{\omega_R}\right) \times E(s)}{\left(1 + \frac{s}{\omega_p}\right) \times \left(1 + \frac{s}{Q_L \times \omega_L} + \frac{s^2}{\omega_L^2}\right)} \]  

Duty cycle:

\[ D = \frac{V_{out} - V_{in}}{V_{out}} \]
DC-Gain:
\[ A_{VC} = \frac{V_{out} \times (1 - D)}{2 \times I_{out} \times A_s \times R_s} \]  \hspace{1cm} (42)

Load pole:
\[ \omega_p = \frac{2}{C_{out} \times R_{out}} \]  \hspace{1cm} (43)

RHPZ:
\[ \omega_R = \frac{V_{out} \times (1 - D)^2}{I_{out} \times L} \]
\[ \omega_L = \pi \times f_{\text{switch}} \]  \hspace{1cm} (44)

With \( V_{\text{slope}} \):
\[ s_e = V_{\text{slope}} \times f_{\text{switch}} \]  \hspace{1cm} (45)

With SLM:
\[ s_e = \frac{S_{LM} \times V_{out} \times A_s \times R_s}{L} \]
\[ s_n = \frac{V_{in} \times A_s \times R_s}{L} \]
\[ Q_L = \frac{1}{\pi \times \left[ 1 + \frac{s_e}{s_n} \right] \times (1 - D) - 0.5} \]  \hspace{1cm} (46)

11.2.5 Transfer Function CMC Inverting Buck-Boost Power Stage

\[ \frac{\hat{V}_{out}}{\hat{V}_c} = A_{VC} \times \frac{1 - \frac{s}{\omega_R}}{1 + \frac{s}{\omega_p}} \times \frac{s}{Q_L \times \omega_L} + \frac{s^2}{\omega_L^2} \]  \hspace{1cm} (47)

Duty cycle:
\[ D = \frac{-V_{out}}{-V_{out} + V_{in}} \]  \hspace{1cm} (48)

Load pole:
\[ \omega_p = \frac{1 + D}{C_{out} \times R_{out}} \]  \hspace{1cm} (49)
11.2.6 Transfer Function CMC Forward Power Stage

For interleaved topologies like Push-Pull, Half-Bridge, or Full-Bridge, twice as much FET switching frequency must be used for calculations because the output inductor "sees" twice the FET switching frequency.

\[
H(s) = A_{VC} \times \frac{E(s)}{\left(1 + \frac{s}{\omega_p}\right) \left(1 + \frac{s}{Q_L \times \omega_L} + \frac{s^2}{\omega_L^2}\right)}
\]

Duty cycle:

\[
D = \frac{V_{out} \times N_p}{V_{in} \times N_s}
\]

DC-Gain:

\[
A_{VC} = \frac{V_{out} \times A_s \times R_s}{I_{out} \times R_{out}} \times \frac{N_p}{N_s}
\]

Load pole:

\[
\omega_p = \frac{1}{C_{out} \times R_{out}}
\]

\[
\omega_L = \pi \times f_{\text{switch}}
\]

With \( V_{\text{slope}} \):

\[
s_e = V_{\text{slope}} \times f_{\text{switch}}
\]
With SLM:

\[
S_e = \frac{\text{SLM} \times V_{\text{out}} \times \frac{N_p}{N_s} \times A_s \times R_s}{L \times \left(\frac{N_p}{N_s}\right)^2}
\]

\[
S_n = \frac{V_{\text{in}} \times \frac{N_s}{N_p} - V_{\text{out}}}{L} \times A_s \times R_s
\]

\[
Q_L = \frac{1}{\pi \times \left[1 + \frac{S_e}{S_n}\right] \times (1 - D) - 0.5}
\]

(58)

**11.2.7 Transfer Function CMC Flyback Power Stage**

\[
H(s) = A_{VC} \times \left(1 - \frac{s}{\omega_R}\right) \times E(s)
\]

\[
H(s) = \frac{1}{1 + \frac{s}{\omega_p} \times \left(1 + \frac{s}{Q_L \times \omega_L + \frac{s^2}{\omega_L^2}}\right)}
\]

(59)

Duty cycle:

\[
D = \frac{V_{\text{out}} \times \frac{N_p}{N_s}}{V_{\text{in}} + V_{\text{out}} \times \frac{N_p}{N_s}}
\]

(60)

DC-Gain:

\[
A_{VC} = \frac{V_{\text{out}} \times (1 - D)}{I_{\text{out}} \times (1 + D) \times A_s \times R_s \times \frac{N_p}{N_s}}
\]

(61)

Load pole:

\[
\omega_p = \frac{1 + D}{C_{\text{out}} \times R_{\text{out}}}
\]

(62)

RHPZ:

\[
\omega_R = \frac{V_{\text{out}} \times (1 - D)^2}{I_{\text{out}} \times L \times D} \times \left(\frac{N_p}{N_s}\right)^2
\]

\[
\omega_L = \pi \times f_{\text{switch}}
\]

(63)

With \(V_{\text{slope}}\):

\[
s_e = V_{\text{slope}} \times f_{\text{switch}}
\]

(64)
With SLM:

\[ s_e = \frac{S_{LM} \times V_{out} \times N_p \times A_s \times R_s}{N_s \times L} \]

\[ s_n = \frac{V_{in} \times A_s \times R_s}{L} \]

\[ Q_L = \frac{1}{\pi \times \left[ 1 + \frac{s_e}{s_n} \right] \times (1 - D) - 0.5} \]

(65)

11.2.8 Transfer Function When Using an Optocoupler

Isolated power supplies incorporate an additional pole in the transfer function due to the limited bandwidth of the optocoupler:

\[ O(s) = \frac{1}{1 + \frac{s}{\omega_{opto}}} \]

\[ \omega_{opto} = 2 \times \pi \times f_{opto} \]

(66)

When the forward and flyback power stages are operating with Zener diode clamped isolated compensation, the transfer function for the power stage is as shown in Equation 67:

\[ \frac{\dot{v}_{out}}{\dot{v}_c} = H(s) \times O(s) \]

(67)

When the forward and flyback power stages are used without Zener diode clamped isolated compensation, the transfer function for the power stage is different:

\[ \frac{\dot{v}_{out}}{\dot{v}_c} = \frac{H(s) \times O(s)}{H(s) \times O(s) + 1} \]

(68)

11.2.9 Transfer Function Type II Compensation Network

Figure 14 is a schematic of a Type II compensation network.

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Figure 14. Schematic of a Type II Compensation Network
\[ \frac{\hat{v}_c}{\hat{v}_\text{out}} = - \frac{A_{\text{VM}} \times \omega_{\text{ZEA}}}{s} \left( 1 + \frac{s}{\omega_{\text{ZEA}}} \right) \left( 1 + \frac{s}{\omega_{\text{HF}}} \right) \]  

DC-Gain:
\[ A_{\text{VM}} = \frac{R_{\text{COMP}}}{R_{\text{FBT}}} \]  

Compensation zero:
\[ \omega_{\text{ZEA}} = \frac{1}{R_{\text{COMP}} \times C_{\text{COMP}}} \]  

Compensation pole:
\[ \omega_{\text{HF}} = \frac{1}{R_{\text{COMP}} \times C_{\text{HF}}} \]  

With additional feed-forward capacitor in parallel with \( R_{\text{FBT}} \):
\[ \omega_{\text{ZFF}} = \frac{1}{R_{\text{FBT}} \times C_{\text{CFF}}} \]  
\[ \omega_{\text{PFF}} = \frac{1}{\left( \frac{1}{R_{\text{RFBB}}} + \frac{1}{R_{\text{RFBT}}} \right) \times C_{\text{FF}}} \]  

### 11.2.10 Transfer Function Type II Transconductance Compensation Network

Figure 15 is a schematic of a Type II transconductance compensation network.

![Figure 15. Schematic of a Type II Transconductance Compensation Network](image)

\[ \frac{\hat{v}_c}{\hat{v}_\text{out}} = - \frac{A_{\text{VM}} \times \omega_{\text{ZEA}}}{s} \left( 1 + \frac{s}{\omega_{\text{ZEA}}} \right) \left( 1 + \frac{s}{\omega_{\text{HF}}} \right) \]  

(74)
DC-Gain:
\[
A_{VM} = \frac{R_{FBB}}{R_{FBB} + R_{FBT}} \times G_m \times R_{COMP}
\] (75)

Compensation zero:
\[
\omega_{ZEA} = \frac{1}{R_{COMP} \times C_{COMP}}
\] (76)

Compensation Pole:
\[
\omega_{HF} = \frac{1}{R_{COMP} \times C_{HF}}
\] (77)

With additional feed-forward capacitor in parallel with \(R_{FBT}\):
\[
\omega_{ZFF} = \frac{1}{R_{FBT} \times C_{OFF}}
\]
\[
\omega_{PFF} = \frac{1}{\left(\frac{1}{R_{RFBB}} + \frac{1}{R_{RFBT}}\right) \times C_{FF}}
\] (78)

11.2.11 Transfer Function Isolated Type II Compensation Network With a Zener Clamp

Figure 16 is a schematic of an isolated Type II compensation network with a Zener clamp.

![Figure 16. Schematic of an Isolated Type II Compensation Network With a Zener Clamp](image)

\[
\frac{\hat{V}_C}{\hat{V}_out} = - \frac{A_{VM} \times \omega_{ZEA}}{S} \times \frac{1 + \frac{S}{\omega_{ZEA}}}{1 + \frac{S}{\omega_{HF}}}
\] (79)
DC-Gain:

\[ A_{VM} = CTR \times \frac{R_P}{R_D} \]  

(80)

Power Stage Designer uses a constant value of 1 for CTR.

Compensation zero:

\[ \omega_{ZEA} = \frac{1}{R_{COMP} \times C_{COMP}} \]  

(81)

Compensation pole:

\[ \omega_{HF} = \frac{1}{R_{COMP} \times C_{HF}} \]  

(82)

11.2.12 Transfer Function Isolated Type II Compensation Network Without a Zener Clamp

Figure 17 is a schematic of an isolated Type II compensation network without a Zener clamp.

\[ \frac{\hat{v}_C}{\hat{v}_{out}} = -\frac{A_{VM} \times \omega_{ZEA}}{s} \times \frac{1 + \frac{s}{\omega_{ZEA}}}{1 + \frac{s}{\omega_{HF}}} \]  

(83)

DC-Gain:

\[ A_{VM} = CTR \times \frac{R_P}{R_D} \]  

(84)

Power Stage Designer uses a constant value of 1 for CTR.

Compensation Zero:

\[ \omega_{ZEA} = \frac{1}{R_{COMP} \times C_{COMP}} \]  

(85)
Compensation pole:

\[ \omega_{HF} = \frac{1}{R_{COMP} \times C_{HF}} \]  

(86)

11.2.13 Transfer Function Type III Compensation Network

Figure 18 is a schematic of a Type III compensation network.

Figure 18. Schematic of a Type III Compensation Network

\[ \frac{\hat{V}_c}{\hat{V}_{out}} = -\frac{A_{VM} \times \omega_{ZEA}}{S} \times \left( \frac{1 + \frac{S}{\omega_{ZEA}}}{1 + \frac{S}{\omega_{PFF}}} \right) \times \left( 1 + \frac{S}{\omega_{ZFF}} \right) \]  

(87)

DC-Gain:

\[ A_{VM} = \frac{R_{COMP}}{R_{FBT}} \]  

(88)

Compensation zero 1:

\[ \omega_{ZEA} = \frac{1}{R_{COMP} \times C_{COMP}} \]  

(89)

Compensation zero 2:

\[ \omega_{ZFF} = \frac{1}{R_{FBT} \times C_{FF}} \]  

(90)

Compensation pole 1:

\[ \omega_{PFF} = \frac{1}{R_{FF} \times C_{FF}} \]  

(91)

Compensation pole 2:

\[ \omega_{HF} = \frac{1}{R_{COMP} \times C_{HF}} \]  

(92)
NOTE: Loop Calculator Tips

A Type I compensation network can be simulated by choosing a Type II compensation (Type II, Type II isolated with a Zener clamp, Type II isolated with inner loop) and setting \( R_{\text{COMP}} \) equal to \( R_{\text{FBT}} \). The crossover frequency depends on the value of \( C_{\text{COMP}} \). Set \( C_{\text{HF}} \) equal to \( C_{\text{COMP}} \).

12 Additional Information

The following list contains references to additional information for various topics in this user's guide.

3. Keogh, Bernard; Cohen, Isaac; Flyback transformer design considerations for efficiency and EMI, Texas Instruments Power Supply Design Seminar SEM2200, 2016/2017 (see Section 5)
4. Dinwoodie, Lisa; Design Review: Isolated 50-Watt Flyback Converter Using the UCC3809 Primary Side Controller and the UC3965 Precision Reference and Error Amplifier (see Section 5)
5. Dinwoodie, Lisa; Application Report: UCC38C44 12-V Isolated Bias Supply (see Section 5)
6. Betten, John; Power Tips: Calculate an R-C snubber in seven steps (see Section 6)
7. Sheehan, R.; Diana, L.; Switch-mode power converter compensation made easy, Texas Instruments Power Supply Design Seminar SEM2200, 2016/2017 (see Section 11.2)
9. Compensating the (often missed) Inner and Outer Control Loops using the TL431 by Robert Kollman and John Betten. Power Electronic Technology Conference, Power Systems World 2002, Chicago (see Section 11.2)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (November 2017) to A Revision Page

• Changed fourth line of Equation 11. ........................................................................................................ 7
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