AN1452

Using the MCP19035 Synchronous Buck Converter Design Tool

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INTRODUCTION

The MCP19035 is a high-performance, highly integrated, synchronous buck controller IC, packaged in a space-saving, 10-pin 3x3mm DFN package. Integrated features include high- and low-side MOSFET drivers, fixed-frequency voltage-mode control, internal oscillator, reference voltage generator, overcurrent protection circuit for both the high- and low-side switches, Power Good indicator and overtemperature protection. The development of a complete, high-performance synchronous buck converter requires a minimum number of external components. Some design effort is still necessary to calculate all the external component's (inductor, MOSFETs, capacitors, compensation network) values and parameters.

This application note familiarizes the designer with Microchip's MCP19035 Synchronous Buck Converter Design Tool. Microchip Technology Inc. provides this design tool to minimize design effort and to help the designer estimate the static (i.e., the efficiency) and dynamic (load step response) performance, and the behavior of the step-down voltage regulator implemented with the MCP19035 controller.

BACKGROUND

The Synchronous Buck Converter

The synchronous buck converter is an improved version of the classic, non-synchronous buck (step-down) converter. This topology improves the low efficiency of the classic buck converter at high currents and low-output voltages. Figures 1 and 2 illustrate the power trains for the classic buck, and synchronous buck converter.

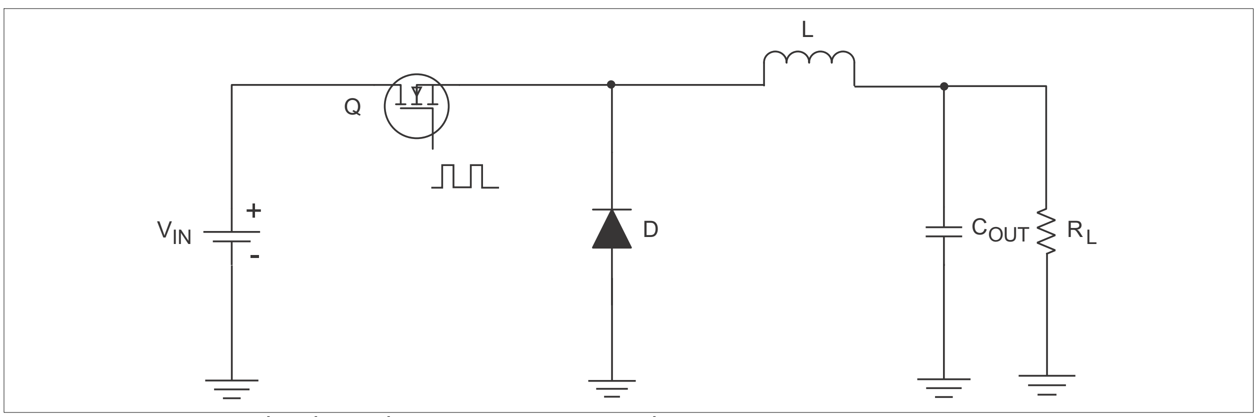


FIGURE 1: *Classic Buck Converter Power Train.*

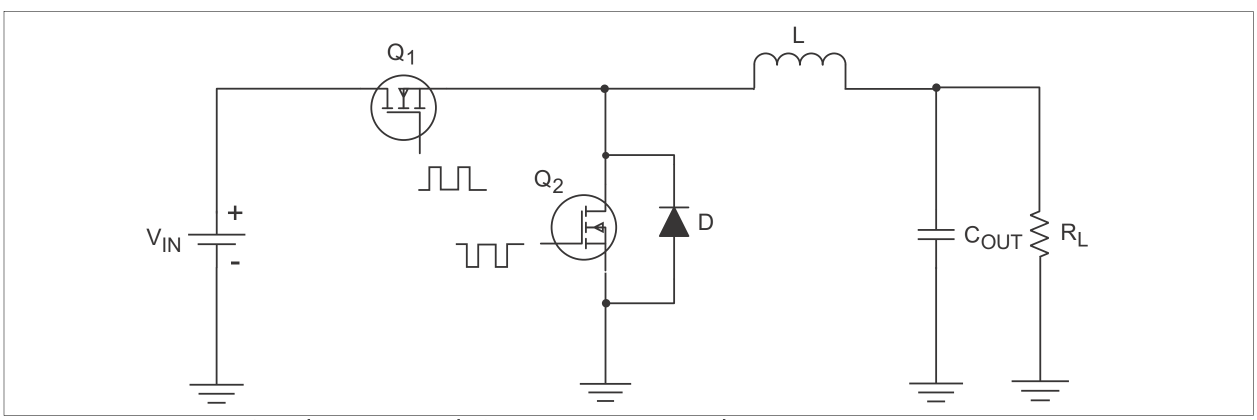


FIGURE 2: *Synchronous Buck Converter Power Train.*

The freewheeling diode of the classic buck converter is replaced with a MOS transistor in the synchronous buck converter. This greatly reduces the conduction losses when the converter operates at high-currents with low-output voltages.

Since the synchronous buck converter is developed to deliver high output currents, it will mainly operate in the Continuous Current Mode (CCM). This application note assumes that the synchronous buck converter only operates in the CCM mode.

The design process for a synchronous buck voltage regulator is split into two phases. In the first phase, the electrical parameters of the power train components (inductor, MOSFETs and capacitors) are calculated based on the target application needs provided by the power supply designer. Further, this design tool can estimate the power components' losses based on the parameters provided by the designer.

In the second phase, the design tool analyzes the AC (small signal) frequency response of the system and proposes a set of component values for the compensation network. The designer has the option to adjust the value of these components, if the frequency response of the compensated system does not meet the design targets.

The MCP19035 synchronous buck controller implements the voltage-mode PWM control. For this kind of control strategy, a Type-III Compensation system is recommended.

Based on these input parameters, the Design Tool calculates the system parameters and the power train component values (inductor, input and output capacitors values).

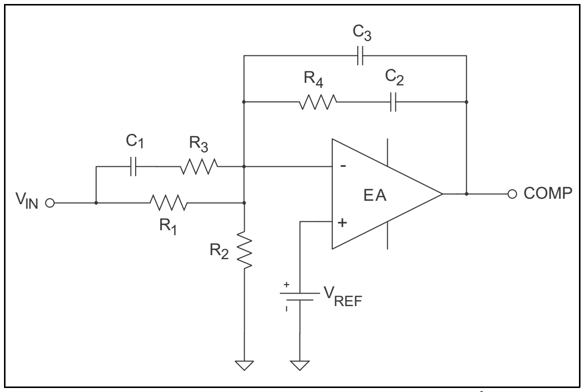


FIGURE 3: *Type-III Compensation Network.*

Appendix A: "List of the Design Tool Formulas" lists the equations used by this design tool. *"Fundamentals of Power Electronics"* [**1**] provides all the theoretical background for the synchronous buck converter operation.

THE MCP19035 SYNCHRONOUS BUCK CONVERTER DESIGN TOOL

Design Tool Input

In the first tab of the Design Tool, the designer provides the system input parameters, including the input and output voltages, maximum output current, switching frequency, input voltage ripple and the reference voltage. Also, the step load parameters must be provided here. An example of the input parameters are summarized in Figure 4.

Input Parameters for Design				
Parameter	**Designator**		**Units**	**Notes**
Input Voltage	V_{IN}	14	V	$5V \le V_{IN} \le 30V$
Output Voltage	V_{OUT}	1.8	V	
Output Current	I_{OUT}	10	A	
Switching Frequency	Fs	600000	Hz	Fs = 300 kHz or 600 kHz
Input Voltage Ripple	V_{RIN}	0.2	V	
Reference Voltage	V_{REF}	0.6	V	
Step Load Parameters				
I_{OH}	I_{OH}	7.5	A	
I_{OL}	I_{OL}	2.5	A	
Output Voltage Overshoot		0.1	V	

FIGURE 4: *Input Parameters Table.*

The second tab of the Design Tool summarizes the system parameters. The Power Train Components table contains two color-marked columns:

- **Suggested Values** (green highlight) – shows the values calculated by the Design Tool
- **Standard Values** (yellow highlight) – the designer completes these fields with the available standard component values

To minimize error and ensure the best possible representation of the system's performance, all further calculations are done based on the user-input standard values of the power train components.

Power Train Components Values (calculated)			
Component	**Suggested Values**	**Standard Values (**)**	**Units**
Inductor Value	0.87	1	µH
C_{OUT}(*)	135.1	200	µF
C_{IN}	10	20	µF
C_{BOOT}	0.276	0.33	µF
* C_{OUT} is calculated based on standard value for inductor and not for suggested value			
** Must be filled by the designer			

FIGURE 5: *The Power Train Components Values Table.*

The Design Tool calculates the RMS currents for the inductor, high- and low-side MOSFETs, and both input and output capacitors. Using these RMS currents the designer determines the power train component's parameters (MOSFETs, inductor and capacitors) following the recommendations from the MCP19035 data sheet. Components' parameters are then manually entered into the Power Train Components Parameter table (Figure 6). Based on these parameters, the Design Tool estimates the losses and the expected efficiency of the converter (Figure 7).

The R_{DSON}, total gate charge and reverse recovery charge of the body diode parameters are available in the MOSFET's data sheet. Refer to the MCP19035 Data Sheet for further details on MOSFETs' selection.

The total conduction time for the body diode will vary between 20 ns (set by the internal logic of the MCP19035) and a maximum value that depends on the MOSFET's type for the MCP19035 version with adaptive Dead Time option. The total conduction time for the body diode cannot be accurately determined from the beginning of the design. The designer can initially use the 40 ns value. For the fixed Dead Time option of MCP19035, optimized to drive Microchip's MOSFETs, this value is fixed to 12 ns.

The DC resistance of the inductor and the equivalent series resistance (ESR) of the capacitors are also available in each component data sheet.

Power Train Components Parameters			
Component Parameter	**Designator**		**Units**
High side MOSFET			
$R_{DS(ON)}$	$R_{DS(ON)HS}$	6	mΩ
Total gate charge	Q_{GATEHS}	13.8	nC
Low side MOSFET			
$R_{DS(ON)}$	$R_{DS(ON)LS}$	2.5	mΩ
Total gate charge	Q_{GATELS}	31	nC
Total Conduction Time for the Body Diode	t_{BD}	12	ns
Reverse Recovery Charge of the Body Diode	Q_{RR}	35	nC
Inductor DC Resistance	L_{DCR}	2	mΩ
C_{IN} ESR		10	mΩ
C_{OUT} ESR		5	mΩ

FIGURE 6: *Power Train Components Parameters Table.*

The Design Tool estimates the losses and the final efficiency of the converter (see the table in Figure 7). The designer can modify several parameters of the power train components in an effort to optimize the efficiency of the converter. The estimated efficiency will depend on the accuracy of the parameters. Some difference between the predicted value and the measured value should be expected. Certain types of losses (for example, hysteresis losses of the inductor) are not calculated by the Design Tool. Refer to the inductor data sheet for details regarding these types of losses.

Estimated System Losses		
High side MOSFET losses		
Conduction losses	0.08	W
Switching losses	1.1592	W
Total losses	1.2392	W
Low Side MOSFET losses		
Conduction losses	0.2	W
Body diode conduction losses	0.0504	W
Body diode reverse recovery losses	0.147	W
Total losses	0.3974	W
Controller losses	0.4	W
Inductor conduction losses	0.2	W
C_{OUT} losses	0.015	W
C_{IN} losses	0.05	W
Total losses	2.3016	W
Estimated Efficiency at Full Load	88.7	%

FIGURE 7: *Losses and Expected Efficiency Table.*

Loop Compensation

The next step in the design is to stabilize the control loop. On the third tab, the Design Tool calculates the values of the compensation network components according with the design procedure described in the MCP19035 data sheet. The designer can also analyze the stability and the dynamic performance of the converter using the Frequency Domain Analysis tab in the Design Tool.

Bode Plots

The Bode plots method is an important engineering tool that can be used for frequency domain analysis of the closed loop systems. Stability and dynamic performance of closed-loop systems can also be estimated using these plots. A Bode plot is the graph representing the magnitude and/or phase of a transfer function, or other complex-domain quantity versus frequency. The magnitude, expressed in decibels, and the phase, expressed in degrees, are plotted on a logarithmic frequency scale.

If H(s) is the transfer function of a linear, time-invariant system, the magnitude and phase are shown in the following equations:

EQUATION 1: GAIN

$$G[dB] = 20 \times \log|H(s)|$$

EQUATION 2: PHASE

$$Phase(H(s)) = atan\frac{Im(H(s))}{Re(H(s))}$$

The gain and phase can now be plotted on a logarithmic frequency scale. These are the Bode plots of the given transfer function.

Similarly, if the converter closed-loop transfer function is known, the Bode plots can be used to analyze the stability and dynamic performance of the system.

The Design Tool uses the Average Model of the buck converter developed in *"Fundamentals of Power Electronics"*[1]. The frequency response of the compensated system is obtained by multiplying the frequency response of the power train with the frequency response of the compensator (see Equation 3).

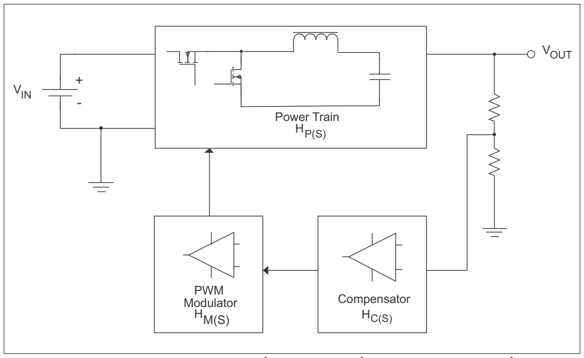


FIGURE 8: *The Synchronous Buck Regulator System.*

EQUATION 3: FREQUENCY RESPONSE OF THE COMPENSATED SYSTEM

$$H_S(s) = H_P(s) \times H_M(s) \times H_C(s)$$

The Design Tool plots the Bode plots for power train, compensation circuit and compensated converter.

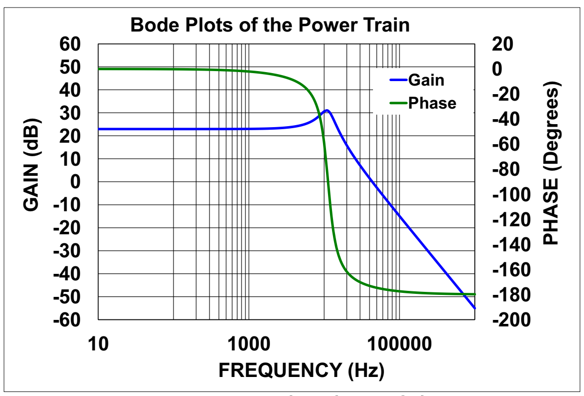


FIGURE 9: *Bode Plots of the Power Train.*

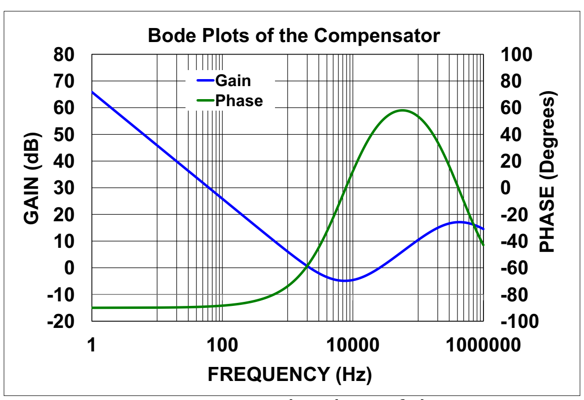


FIGURE 10: *Bode Plots of the Compensation Circuit.*

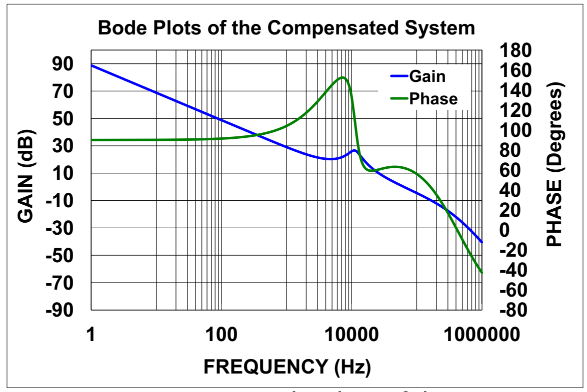


FIGURE 11: *Bode Plots of the Compensated System.*

The designer can now estimate the stability and dynamic performance of the system by inspecting the Bode plots.

The first parameter of interest is the system's crossover frequency. The crossover frequency is the point where the gain of the system becomes 0 dB. A higher crossover frequency means a better dynamic performance of the system (better transient response). However, due to the stability criteria, this crossover frequency cannot be set infinitely high.

Phase margin is the second parameter of interest, and directly related to the stability of the closed loop system. In a closed loop system that uses negative feedback, the phase margin is defined as the difference between the phase at the crossover frequency and 0°.

The third parameter is the gain margin. This parameter is also related to the system stability and will indicate how far the system is from the instability point (0 dB). The gain margin is defined as the amount of gain that must be added to the system gain to reach the 0 dB point, calculated at the point where the phase reaches 0°.

The Design Tool automates the calculation of these three parameters and plots the results. The designer can use these parameters to evaluate the stability of the closed loop system.

Fcrossover	63000	Hz
Phase Margin	62.1	Degrees
Gain Margin	22.9	dB

FIGURE 12: *Closed Loop System Parameters.*

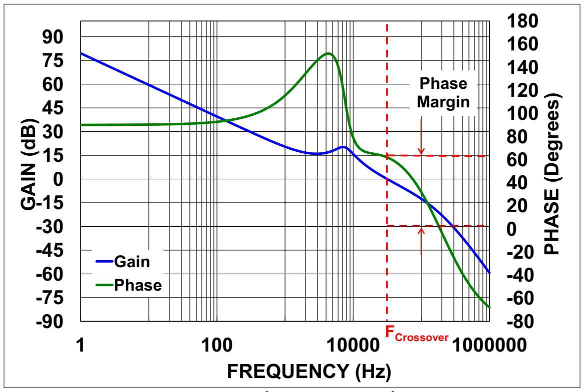


FIGURE 13: *Phase Margin.*

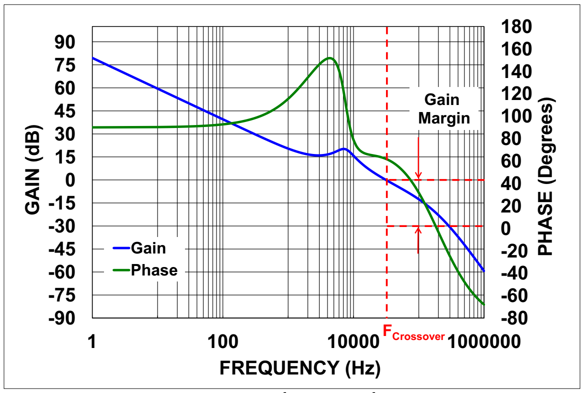


FIGURE 14: *Gain Margin.*

Stability Criterion

The designer can estimate if the closed loop system is stable by verifying if the phase and gain margin fulfills the Nyquist stability criterion. The criterion states that a closed loop system is asymptotically stable if:

- Phase margin is greater than 0°
- Gain margin is greater than 0 dB

However, for a real system where noise and high-order effects are present, these limits must be modified according to the following rules:

- Phase margin must be greater than 45°
- Gain margin must be greater than 6 dB

The larger the values, the better stability. At the same time, the system becomes slower, with poor dynamic response to an external perturbation. A system with lower phase and gain margins offer a faster transient response, but is more sensitive to noise and can become unstable.

Noise, Compensation And Stability in Practical Systems

The Design Tool uses an ideal, linearized model that is not able to include and analyze all phenomena present within a real-world, step-down PWM converter application. Some effects, such as the delays introduced by the PWM modulator, Error Amplifier bandwidth and switching elements (MOSFETs), can produce additional phase lag, decreasing the phase margin of the compensated system. A safe way to avoid these effects is to design the regulator with a phase margin greater than 50° using the Design Tool.

The power train passive components (inductor, input and output filter capacitors) may have large tolerances. The values are also affected by the operating conditions: inductor's inductance varies with the current, and the capacitance of the ceramic capacitors varies with the operating voltage. It is highly recommended to check the stability of the system for all limits of components tolerances. In general, the inductance of the inductor drops when the current increases. This variation also depends on the magnetic material that is used for the core. The capacitance of the ceramic capacitor decreases if the voltage across the terminals increases. All the variation curves are provided in the component's data sheet and must be verified by the designer.

As previously mentioned, setting the crossover frequency high results in faster transient response. If the crossover frequency is too high, the system control loop can become sensitive to noise even if it is still stable (i.e., the phase margin exceeds 45°). The noise that passes through the loop will adversely affect the PWM modulator, producing a jitter on the high and low-side driver's signals and impact the output voltage ripple.

Figure 15 captures this noisy behavior. The low and high-side driver's signals have jitter, and the output voltage ripple is higher than in normal operation. This behavior can also occur at high input voltages because the gain of the PWM modulator increases with the input voltage. The designer must reduce the crossover frequency of this system to avoid this behavior at high input voltages. Notice that this noisy behavior may also occur when the system runs near the Critical Conduction Mode, where the current in the inductor reaches zero. In this case, the power train becomes a first-order system (versus a second-order system, typical for voltage-mode control PWM buck regulators) resulting in an overly-aggressive gain profile of the Type-III compensator, which introduces noisy behavior. In practice, however, this instability will not affect the performance of the system, and can be safely ignored.

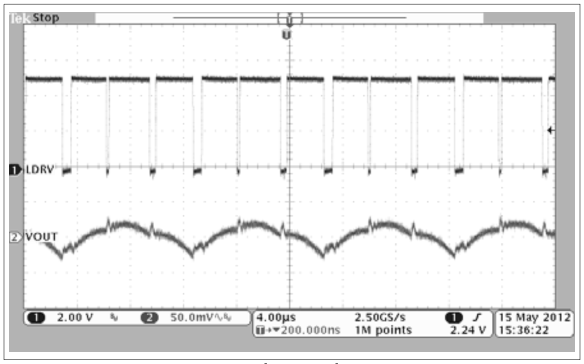


FIGURE 15: The Noisy System.

The designer must verify that the converter is stable over the entire input voltage range. Figure 16 shows an unstable system. A sinusoidal oscillation is superimposed over the output voltage. This sinusoidal oscillation has a frequency equal to the system crossover frequency. The amplitude of this sinusoidal oscillation will vary with the input voltage and output current. This kind of instability is always related to the compensation loop, and is mostly produced by low phase and gain margins.

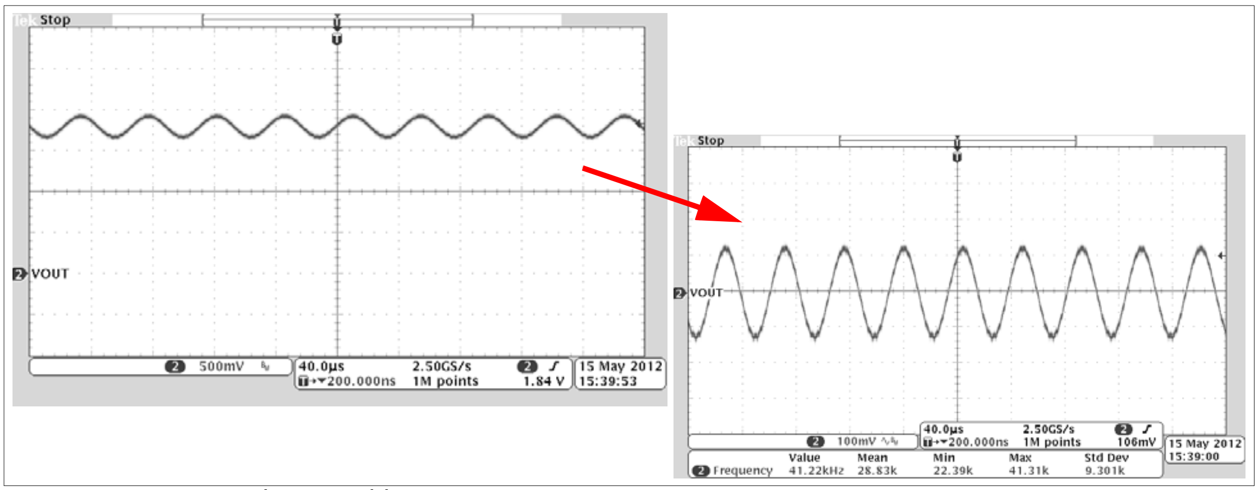
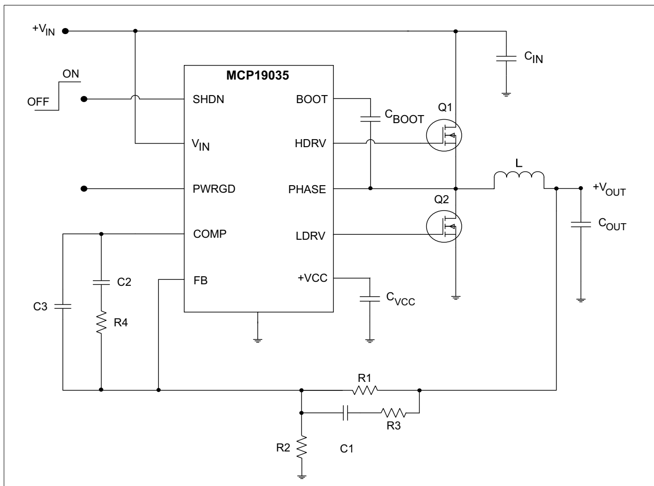


FIGURE 16: The Unstable System.

Design Summary

The fourth tab of the Design Tool provides the design summary. This page lists all the values for the power train and compensation network components, together with a typical application schematic. The frequency analyses results and the estimated, full-load efficiency are also plotted.



L	1	µH
C_{IN}	20	µF
C_{OUT}	200	µF
C_{BOOT}	0.33	µF

R1	20	kΩ
R2	10	kΩ
R3	0.75	kΩ
R4	8.2	kΩ
C1	0.68	nF
C2	3.9	nF
C3	0.033	nF

$F_{CROSSOVER}$	63000	Hz
Phase Margin	62.1	Degrees
Gain Margin	22.9	dB

Estimated Efficiency at Full Load	88.7	%

FIGURE 17: The Design Summary.

STEP-BY-STEP DESIGN EXAMPLE

This section presents a practical design example using the MCP19035 Synchronous Buck Converter Design Tool.

The project implies the design of a step-down, synchronous buck converter using the MCP19035. The system has the following input parameters:

TABLE 1: CONVERTER PARAMETERS

Parameter	Value	Unit
Input Voltage Range	8 – 14	V
Output Voltage	1.8	V
Maximum Output Current	10	A
Input Voltage Ripple	0.2	V
I_{OH} (Step Load High Value)	7.5	A
I_{OL} (Step Load Low Value)	2.5	A
Output Voltage Overshoot	0.1	V

For the input voltage, enter the maximum value. This will ensure that the current ripple in the inductor will be maintained at 30% of the maximum output current at high-input voltages.

Due to the space constraints of the final application, the converter must be compact, while maintaining high efficiency. The load that must be powered from this converter will produce a step load between 2.5A and 7.5A. The maximum output voltage overshoot during step load must be lower than 100 mV.

For this application, the designer may choose the 600 kHz switching frequency version with optimized dead time. The higher switching frequency will help minimize the power train component's size, while the optimized dead time option will increase the system's efficiency.

Step 1: Introducing the Parameters

Start the MCP19035 Synchronous Buck Converter Design Tool. All the input parameters of the converter are introduced in the table on the first tab of the Design Tool.

TABLE 2: INPUT PARAMETERS FOR DESIGN

Parameter	Designator	Value[1]	Unit	Notes
Input Voltage	V_{IN}	14	V	5V = V_{IN} = 30V
Output Voltage	V_{OUT}	1.8	V	
Output Current	I_{OUT}	10	A	
Switching Frequency	Fs	600000	Hz	Fs = 300 kHz or 600 kHz
Input Voltage Ripple	V_{RIN}	0.2	V	
Reference Voltage	V_{REF}	0.6	V	
Step Load Parameters				
Step Load High	I_{OH}	7.5	A	
Step Load Low	I_{OL}	2.5	A	
Output Voltage Overshoot		0.1	V	

Note 1: The values in this column must be filled in by the designer.

Step 2: Calculate the Values

The second page of the Design Tool shows the calculated values for various system parameters, such as RMS currents for low- and high-side MOSFETs, the inductor and the input and output filtering capacitors (Table 3).

Fill in the standard values of the power train according to the recommendations provided by MCP19035's data sheet. For example, the Design Tool calculates an inductor value of 0.87 µH and, based on the recommendations, the next standard value is 1 µH. For the capacitor, it is generally advisable to choose a higher value, because ceramic capacitors have large tolerances and exhibit a negative capacitance variation with voltage across the terminals.

TABLE 3: POWER TRAIN COMPONENTS VALUES (CALCULATED)

Component	Suggested Value	Standard Value(2)	Unit
Inductor Value	0.87	1	µH
C_{OUT}(1)	135.1	200	µF
C_{IN}	10	20	µF
C_{BOOT}	0.276	0.33	µF

Note 1: C_{OUT} is calculated based on the standard value for inductor and not for suggested value.

2: The values in this column must be filled in by the designer

To calculate the value of the bootstrap capacitor (C_{BOOT}), the high-side MOSFET's parameters must be introduced in the Power Train Components Parameters table (Table 4).

Choose the MOSFETs, inductor and filtering capacitor's parameters, based on the RMS currents calculated by the Design Tool and following the recommendations from the MCP19035 data sheet. These parameters must be entered in Table 4 (Power Train Components Parameters table).

Since this application requires high efficiency, Microchip's MCP87050 and MCP87022 MOSFETs will be used. The requested parameters are available in the components' data sheet. These MOSFETs are suitable for use with the optimized dead time version of the MCP19035. In this case, the "Total Conduction Time for the Body Diode" parameter is fixed, and equals 12 ns.

The DC resistance of the inductor and ESRs of the input and output capacitors are entered in the same table. All these parameters will affect the performance of the converter and the designer must carefully select them, in concordance with the MCP19035 data sheet's recommendations.

TABLE 4: POWER TRAIN COMPONENTS PARAMETERS

Parameter	Designator	Value(1)	Unit
High side MOSFET			
$R_{DS(ON)}$	$R_{DS(ON)HS}$	6	mΩ
Total gate charge	Q_{GATEHS}	13.8	nC
Low side MOSFET			
$R_{DS(ON)}$	$R_{DS(ON)LS}$	2.5	mΩ
Total gate charge	Q_{GATELS}	31	nC
Total Conduction Time for the Body Diode	t_{BD}	12	ns
Reverse Recovery Charge of the Body Diode	Q_{RR}	35	nC
Inductor DC Resistance	L_{DCR}	2	mΩ
C_{IN} ESR		10	mΩ
C_{OUT} ESR		5	mΩ

Note 1: The values in this column must be filled in by the designer.

Based on the parameters of the power train components, the Design Tool will estimate the system losses and the efficiency at full load. Note that the losses are affected by the input voltage; the worst case is at maximum input voltage, 14V in this case.

TABLE 5: ESTIMATED SYSTEM LOSSES

Parameter	Value	Unit
High-Side MOSFET losses		
Conduction losses	0.08	W
Switching losses	1.1592	W
Total losses	1.2392	W
Low-Side MOSFET losses		
Conduction losses	0.2	W
Body diode conduction losses	0.0504	W
Body diode reverse recovery losses	0.147	W
Total losses	0.3974	W
Controller losses	0.4	W
Inductor conduction losses	0.2	W
C_{OUT} losses	0.015	W
C_{IN} losses	0.05	W
Total losses	2.3016	W
Estimated Efficiency at Full Load	88.7	%

Step 3: Frequency Domain Analysis

The next step of the design is the frequency domain analysis. This analysis can be performed on the third tab of the Design Tool. The Design Tool calculates the values of the compensation network components according to the procedures described in the MCP19035 data sheet (Table 6).

TABLE 6: COMPENSATION NETWORK CALCULATED VALUES

Calculated Values for the Compensation Network (1)		Units
R1	20	kΩ
R2	10	kΩ
R3	0.75	kΩ
R4	7.62	kΩ
C1	0.71	nF
C2	3.71	nF
C3	0.035	nF

Note 1: The values with yellow background must be filled in by the designer. The ones with green background are calculated by the tool.

Enter the calculated values in the Compensation Network Components table (Table 7).

TABLE 7: COMPENSATION NETWORK COMPONENTS

Compensation Network Components (1)		Units
R1	20	kΩ
R3	0.75	kΩ
R4	8.2	kΩ
C1	0.68	nF
C2	3.9	nF
C3	3.30E-02	nF

Note 1: These values must be filled in by the designer.

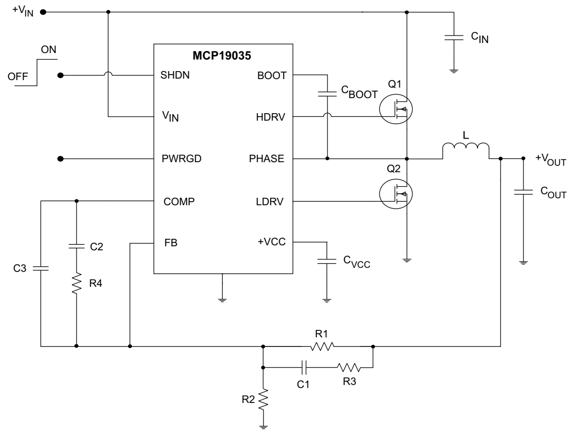
Based on these values, the Design Tool will plot the Bode plots and calculate the crossover frequency, phase and gain margin of the compensated system. Adjust the values of the compensation network components to modify the frequency response of the system. Note that the frequency response of the system is affected by the value of the input voltage. It is advisable to perform the frequency analyses for the entire range of the input voltage. The worst case occurs again at high input voltages because the PWM modulator gain increases with the input voltage.

TABLE 8: SYSTEM PARAMETERS

Parameter	Value	Unit
$F_{Crossover}$	63000	Hz
Phase Margin	62.1	Degrees
Gain Margin	22.9	dB

Step 4: Design Summary

The last tab of the Design Tool shows the summary of the design and the typical application schematic for the synchronous buck regulator, based on the MCP19035 device. The designer can generate the final schematic for the step down regulator with these component's values.



L	1	µH
C_{IN}	20	µF
C_{OUT}	200	µF
C_{BOOT}	0.33	µF

R1	20	kΩ
R2	10	kΩ
R3	0.75	kΩ
R4	8.2	kΩ
C1	0.68	nF
C2	3.9	nF
C3	0.033	nF

$F_{CROSSOVER}$	63000	Hz
Phase Margin	62.1	Degrees
Gain Margin	22.9	dB

Estimated Efficiency at Full Load	88.7	%

FIGURE 18: *The Design Summary.*

REFERENCES

1. Erikson, Robert W. and Maksimovic, Dragan – *"Fundamentals of Power Electronics (Second Edition)"*, ©2001, Springer Science and Business Media, Inc.

APPENDIX A: LIST OF THE DESIGN TOOL FORMULAS

Parameter Name	Equation
Inductor Value (H)(for 30% current ripple)	$L = (V_{INMAX} - V_{OUT}) \times \frac{V_{OUT}}{V_{INMAX}} \times \frac{1}{f_{SW}} \times \frac{1}{0.3 \times I_{OUTMAX}}$
Inductor Peak Current (A) (for 30% current ripple)	$I_{LPEAK} = I_{OUTMAX} + \frac{0.3 \times I_{OUTMAX}}{2}$
Inductor RMS Current (A)	$I_{LRMS} = \sqrt{I_{OUT}^2 + \frac{I_{Ripple}^2}{3}}$
Minimum Capacitance for Input Capacitor (F)	$C_{INMIN} = \frac{I_{OUT} \times D \times (1-D)}{f_{SW} \times (V_{Ripple} - (D \times I_{OUT} \times ESR))}$
RMS Current in the Input Capacitor (A)	$I_{RMS(C_{IN})} = \left(I_{OUT} + \frac{I_{Ripple}}{12}\right) \times \sqrt{D} - \frac{V_{OUT} \times I_{OUT}}{V_{IN}}$
Output Voltage Ripple (V)	$V_{Ripple} = I_{Ripple} \times \left(ESR + \frac{1}{8 \times C_{OUT} \times f_{SW}}\right)$
Output Capacitor Minimum Value (F)	$C_{OUT} = \frac{L \times \lvert I_{OH}^2 - I_{OL}^2 \rvert}{\lvert V_f^2 - V_{OUT}^2 \rvert}$
RMS Value for High-side Current (A)	$I_{RMS\ High\text{-}Side} = \sqrt{D \times \left(I_{OUT}^2 + \frac{I_{Ripple}^2}{12}\right)}$
Conduction Losses for High-side MOSFET (W)	$P_{COND\ High\text{-}Side} = I_{RMS\ High\text{-}Side}^2 \times R_{DS(on)HS(max)}$
Switching Losses for High-side MOSFET (W)	$P_{SW\ High\_Side} = \left(\frac{V_{IN} \times I_{OUT}}{2}\right) \times (t_{s(HL)} + t_{s(LH)}) \times f_{SW}$
Total Power Losses for High-side MOSFET (W)	$P_{Loss\ High\text{-}Side} = P_{COND\ High\text{-}Side} + P_{SW\ High\text{-}Side}$
RMS Current for Low-side MOSFET (W)	$I_{RMS\ Low\text{-}Side} = \sqrt{(1-D) \times \left(I_{OUT}^2 + \frac{I_{Ripple}^2}{12}\right)}$
Conduction Losses for Low-side MOSFET (W)	$P_{COND\ Low\text{-}Side} = I_{RMS\ Low\text{-}Side}^2 \times R_{DS(on)LS(max)}$
Body Diode Conduction Losses (W)	$P_{Loss\ BD} = I_{OUT} \times V_F \times t_{BD} \times f_{SW}$
Body Diode Reverse Recovery Losses (W)	$P_{RR} = \frac{Q_{RR} \times V_{IN} \times f_{SW}}{2}$

APPENDIX A: LIST OF THE DESIGN TOOL FORMULAS (CONTINUED)

Parameter Name	Equation
Total Power Losses for Low-side MOSFET (W)	$P_{Loss} = P_{COND\ Low-Side} + P_{Loss\ BD} + P_{RR}$
Controller Losses (W) (considering that the internal circuitry losses are 0.005W)	$P_{Loss} = V_{IN} \times (0.005 + F_S \times (Q_{Gate,low} + Q_{Gate,high}))$
Inductor Losses (W)	$P_{Loss} = DCR_L \times I^2_{L\ RMS}$
Output Capacitor Losses (W) (for 30% current ripple)	$P_{Loss} = ESR_{COUT} \times \frac{0.3 \times I_{OUT}}{3}$
Input Capacitor losses (W)	$P_{Loss} = ESR_{CIN} \times \left(I_{RMS\ High} - \frac{V_{OUT} \times I_{OUT}}{V_{IN}}\right)^2$
Bootstrap Capacitor (F)	$C_{BOOT} = \frac{Q_{G(Total)}}{\Delta V_{DROOP}}$
Resonant Frequency of the LC Circuit (Hz)	$f_{LC} = \frac{1}{2\pi \times \sqrt{L \times C_{OUT}}}$
PWM Modulator Gain	$A_{MOD} = 20 \times \log\frac{V_{IN}}{\Delta V_{RAMP}} = 20 \times \log V_{IN}$
Quality Factor	$Q = \frac{V_{OUT}}{I_{OUT}} \times \sqrt{\frac{C_{OUT}}{L}}$
Angular Corner Frequency	$\omega_0 = \frac{1}{\sqrt{L \times C_{OUT}}}$
Transfer Function of the Power Train	$G_{VG}(s) = G_0 \times \frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$
Transfer Function of the Type III Compensation Network	$G(s) = -A_0 \times \frac{R_1 + R_3}{R_1 \times R_3 \times C_1} \times \frac{\left(s + \frac{1}{R_4 \times C_2}\right) \times \left(s + \frac{1}{(R_1 + R_3) \times C_1}\right)}{s \times \left(s + \frac{C_2 + C_3}{R_4 \times C_2 \times C_3}\right) \times \left(s + \frac{1}{R_3 \times C_1}\right)}$
Feedback resistor divider (Ω)	$R_2 = \frac{V_{REF} \times R_1}{V_{OUT} - V_{REF}} = \frac{0.6 \times R_1}{V_{OUT} - 0.6}$

APPENDIX A: LIST OF THE DESIGN TOOL FORMULAS (CONTINUED)

Parameter Name	Equation
Capacitor C_1 (F)	$C_1 = \frac{\sqrt{L \times C_{OUT}}}{R_1}$
Resistor R_4 (Ω)	$R_4 = \frac{f_{CO}}{f_{LC}} \times \frac{1}{V_{IN}} \times R_1$
Capacitor C_2 (F)	$C_2 = \frac{2 \times \sqrt{L \times C_{OUT}}}{R_4}$
Capacitor C_3 (F)	$C_3 = \frac{1}{2\pi \times R_4 \times f_{SW}}$
Resistor R_3 (Ω)	$R_3 = \frac{1}{\pi \times C_1 \times f_{SW}}$
Input Power (W)	$P_{IN} = \frac{U_{OUT} \times I_{OUTmax}}{Eff}$
Total converter losses (W)	$P_{Loss} = P_{IN} - P_{OUT}$
Maximum $R_{DS(on)}$ (Ω)	$R_{DS(on)} = \frac{P_{Loss\ High-Side}}{I_{RMS\ High-Side}^2} \times 0.4$

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