AN1385

Dynamic Analysis of the MCP16301 Switch Mode Power Converter Utilizing the MCP16301 Design Analyzer

INTRODUCTION

In a general sense, a power converter can be defined as a device which converts one form of energy into another on a continuous basis. Any storage or loss of energy within such a system while it is performing its conversion function is usually identical to the process of energy translation. There are many types of devices which can provide such a function with varying degrees of cost, reliability, complexity, and efficiency.

The mechanisms for power conversion can take many basic forms, such as those that are mechanical, electrical, or chemical processing in nature. This application note focuses on an inductor based, dc-dc switch mode power converter, the MCP16301. This power converter performs energy translation electrically and in a dynamic fashion. The dynamic behavior directly determines or influences four of the important characteristics of a switch mode power converter:

- Stability of the feedback loop
- Rejection of input voltage ripple and the closely related transient response to input voltage perturbations
- Output impedance and the closely related transient response to load perturbations
- Compatibility with an input EMI filter

Due to the complexity of the operation of a switch mode power converter, predicting its dynamic behavior is not always an easy task. Without accurate predictions, and depending only on building the circuit and performing component iterations until the operation is satisfactory, the engineering cost can easily escalate, schedules can be missed, and the final solution is rarely optimized.

BACKGROUND

The goal of this application note is to provide the analytical tools required to predict the dynamic behavior of the MCP16301 switch mode power converter. The dynamic analysis presented is basically a low-frequency, small-signal analysis, accurate at frequencies up to one-third of the switching frequency. The validity can be extended toward higher frequencies, up to the Nyquist limit of one-half of the switching frequency, by employing a limited discrete time analysis correction factor. In its purest form, discrete time analysis is accurate and applicable both in large and small signal analysis. The penalty is rather complex difference equations and z-domain transfer functions with an absence of physical insight that is so essential in practice. Without the complexity, the small-signal analysis presented can be used to accurately predict, at all dc operating points, (1) the margin of stability of the converter, against closed loop oscillation, and (2) the frequency-domain and time-domain responses to perturbations in the input voltage and/or the output current. Large-signal analysis requires a different set of tools and is beyond the scope of this application note.

The MCP16301 employs a peak current mode control architecture, wherein, a control reference is used to regulate the peak current of the converter directly, simplifying the dynamics of the converter. The inner current loop essentially turns the inductor into a voltage controlled current source, reducing the control-to-output transfer function to a simple single-pole model of a current source feeding a capacitor. However, under certain operating conditions, the current feedback loop can become unstable, and the simple single-pole model cannot predict this event. It has been shown in [1] that a simple extension to the single pole model can be made that accounts for the subharmonic oscillation phenomenon seen in current-mode controlled converters. An approximation to discrete time analysis is combined with the simplicity of pole-zero representation to accurately model the oscillation phenomenon, ramp addition, and control-to-output transfer function.

Reference [1] provides the theoretical background, providing an exhaustive analysis of the buck converter with its associated models and results for fixed frequency, continuous conduction mode operation. In summary, the approximate control-to-output transfer function for the MCP16301 buck converter is given by:

$$\frac{\hat{v}_o}{\hat{v}_c} = \frac{R}{R_i}\frac{1}{1+\frac{RT_s}{L}[m_cD'-0.5]}F_p(s)F_h(s)$$

where

$$F_p(s) = \frac{1 + sCR_c}{1 + \frac{s}{\omega_p}}$$

where

$$\omega_p = \frac{1}{CR} + \frac{T_s}{LC}[m_c D' - 0.5]$$

and

$$F_h(s) = \frac{1}{1 + \frac{s}{\omega_n Q} + \frac{s^2}{\omega_n^2}}$$

where

$$\omega_n = \frac{\pi}{T_s}$$

where

$$Q = \frac{1}{\pi[m_c D' - 0.5]}$$

It is interesting that the discrete time approximation, $F_h(s)$, is common to all converters. The Q in the equation is controlled by the choice of the added slope compensation ramp. The MCP16301 employs a fixed slope compensation ramp.

Therefore, for different output voltages, it is necessary to change the inductor value to ensure the Q of the double pole is one or less, preventing gain peaking at one-half the switching frequency and subsequent subharmonic oscillation.

The slope compensation ramp factor is given by

$$m_c = 1 + \frac{S_e}{S_n}$$

where the slope compensation ramp slope, S_e, is

$$S_e = \frac{V_{pp}}{T_s}$$

and the slope of the sensed current waveform into the PWM controller, S_n, is

$$S_n = \frac{V_{ON}}{L} R_i$$

Setting $Q = 1$ and solving, the amount of slope compensation ramp necessary can be determined. This is usually expressed in terms of the inductor current off-time ramp slope, S_f, as opposed to the inductor current on-time ramp slope, S_n. Solving the equation in terms of S_f yields

$$\frac{S_e}{S_f} = 1 - \frac{0.18}{D}$$

where

$$S_f = \frac{V_{OFF}}{L} R_i$$

and

$$S_n = S_f \frac{D'}{D}$$

The appropriate inductor value can then be determined.

This is different than other suggestions. Some recommend adding as much ramp as the downslope. This is more than is needed, overdamping the system. For the buck converter, in theory, adding one half the downslope cancels all perturbations from input-to-output. In practice, this nulling is never achieved completely, and a small amount of noise makes it impossible.

MCP16301 DESIGN ANALYZER

Design Analyzer Input

The control-to-output transfer function is very useful for design purposes. The MCP16301 Design Analyzer employs all equations necessary to model the dynamic behavior of the converter and predict its response.

Referring to Figure 1, the MCP16301 Design Analyzer is a tool for the designer to quickly and accurately access the stability, efficiency, and margin of the system at various operating conditions. Recommended passive component values are provided. The designer also has the ability to try alternative component values and access their effect on the system. The designer simply enters their operating system parameters of interest and verifies the output.

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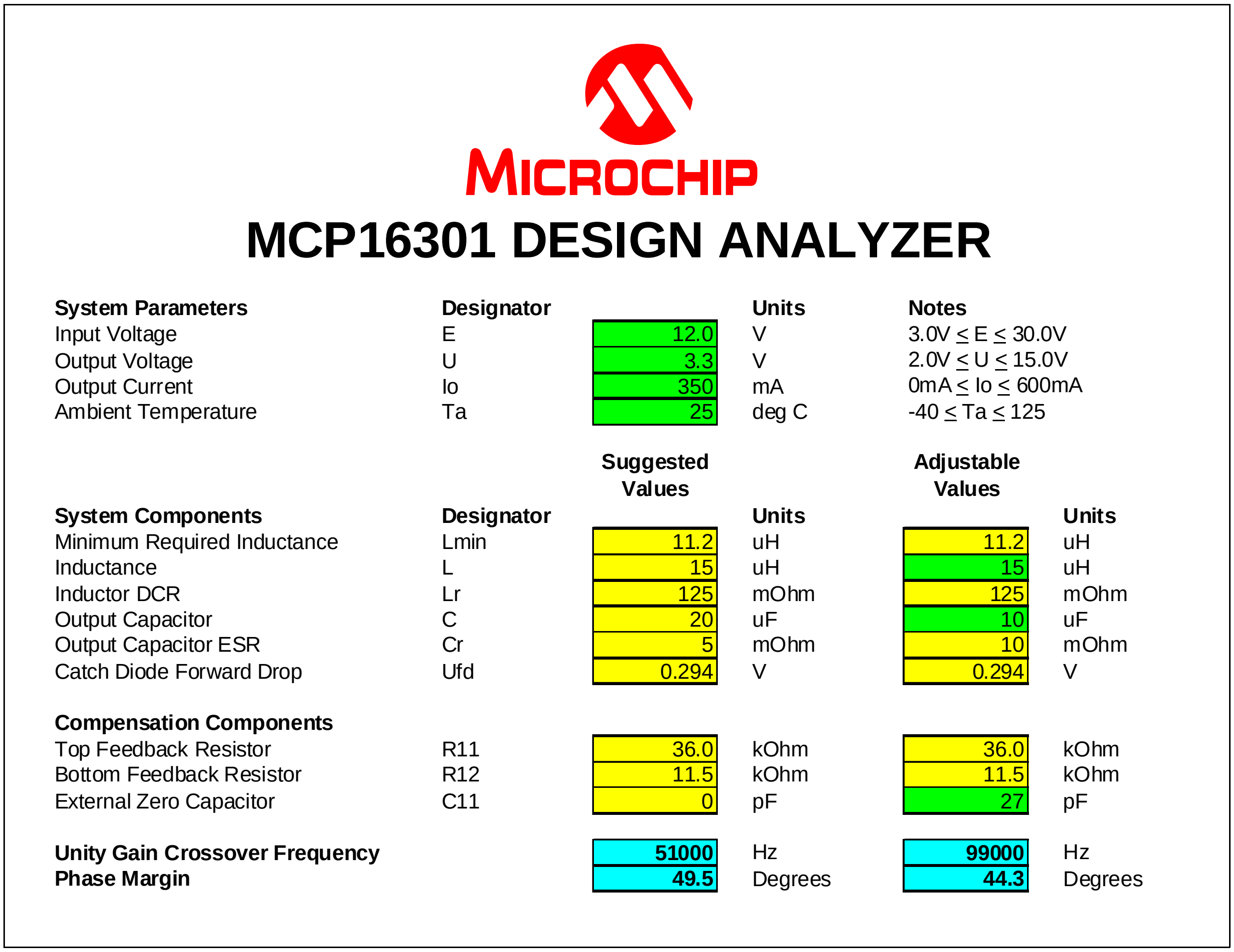

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MCP16301 DESIGN ANALYZER

System Parameters	Designator		Units	Notes
Input Voltage	E	12.0	V	3.0V ≤ E ≤ 30.0V
Output Voltage	U	3.3	V	2.0V ≤ U ≤ 15.0V
Output Current	Io	350	mA	0mA ≤ Io ≤ 600mA
Ambient Temperature	Ta	25	deg C	-40 ≤ Ta ≤ 125

System Components	Designator	Suggested Values	Units	Adjustable Values	Units
Minimum Required Inductance	Lmin	11.2	uH	11.2	uH
Inductance	L	15	uH	15	uH
Inductor DCR	Lr	125	mOhm	125	mOhm
Output Capacitor	C	20	uF	10	uF
Output Capacitor ESR	Cr	5	mOhm	10	mOhm
Catch Diode Forward Drop	Ufd	0.294	V	0.294	V
Compensation Components					
Top Feedback Resistor	R11	36.0	kOhm	36.0	kOhm
Bottom Feedback Resistor	R12	11.5	kOhm	11.5	kOhm
External Zero Capacitor	C11	0	pF	27	pF
Unity Gain Crossover Frequency		**51000**	Hz	**99000**	Hz
Phase Margin		**49.5**	Degrees	**44.3**	Degrees

FIGURE 1: *MCP16301 Design Analyzer User Inputs - Green.*

Design Analyzer Output - Bode Plot

The Bode plot is a method of displaying complex values of circuit gain or impedance. The gain magnitude in dB is plotted versus log frequency. The phase angle is plotted separately against the same log frequency scale.

Bode plots are an excellent tool for analyzing switching power supply closed loop systems. The Bode plot provides good visibility into the gain and phase characteristics of the various loop elements. Calculation of the overall loop is made simply by adding gain in dB and phase in degrees.

Bode's theorem for simple systems, which includes most switching power supplies, states that the phase angle of the gain at any frequency is dependent upon the rate of change of gain magnitude versus frequency.

At this point, some important terms relative to stability analysis are defined:

- **Gain Margin**

  Defined as the difference between unity gain (zero dB) and the actual gain when the phase reaches 180°. The recommended value is -6 dB to –12 dB.

- **Phase Margin**

  Defined as the difference between 180° and the actual phase when the gain reaches unity gain. The recommended value is 45° to 60°.

- **Stability Criteria**

  A commonly used derivative from the above two definitions, in accordance with Bode's theorem, is that if the slope of the gain response as it crosses the unity-gain axis is not more than -6 dB/octave, the phase margin will be greater than 45° and the system will be stable.

No approximations have been made in the Design Analyzer other than those required for linearizing the system. It should be understood that phase shift is caused not only by reactive components, but also by time delay, such as transistor storage time or hold time in a sampling system. Switch delays normally have little effect as long as there is no explicit sample-and-hold function, and the frequencies of interest are well below the switching frequency. For example, the effect of a 1 µs delay in a 100 kHz system is a phase shift of less than 4°. There will also be potential phase lags due to the op amp and parasitic components. Thus, although technically a second-order system could potentially be stable since 180° phase lag is only asymptotically approached, we can expect that this system, as currently defined, will be unstable in practice and, in any case, would suffer serious ringing under any external disturbance.

Figure 2 depicts a Bode plot output example from the Design Analyzer. The S_Gain and S_Phase plots represent the overall system loop with the suggested component values. The A_Gain and A_Phase curves represent the overall system loop with the actual system component values.

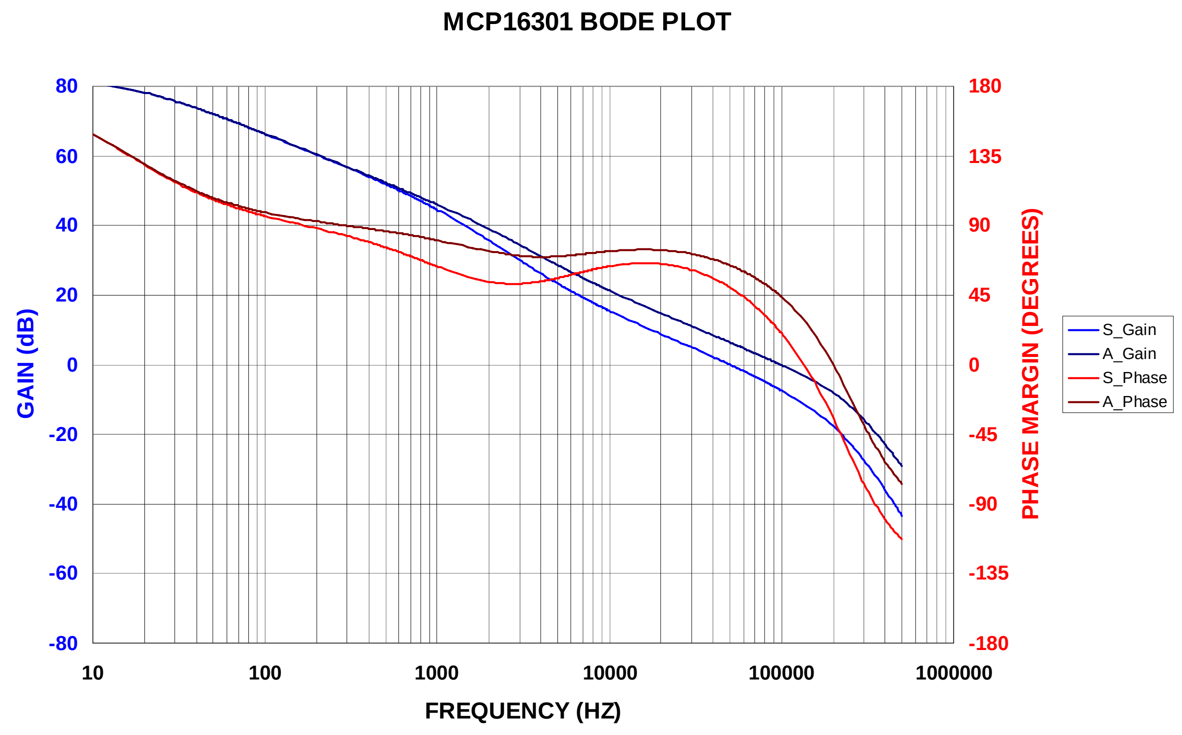

FIGURE 2: *MCP16301 Design Analyzer Bode Plot Output.*

Design Analyzer Output - Efficiency

Switch mode power converters employ a restricted set of components which include inductors, capacitors, transformers, switches, and resistors. How these circuit components are connected is determined by the desired power translation. Resistors introduce undesirable power loss. Since high efficiency is usually an overriding requirement in most applications, resistive circuit elements should be avoided or minimized. Only on rare occasions and for very specific reasons are power consuming resistances introduced into the main power control path. In auxiliary circuits, such as sequence, monitor, and control electronics of total system, high value resistors are common place, since their loss contributions are usually insignificant.

The Design Analyzer provides the calculated efficiency of power conversion implemented with the suggested component values. Figure 3 depicts an Efficiency versus Output Current graph example.

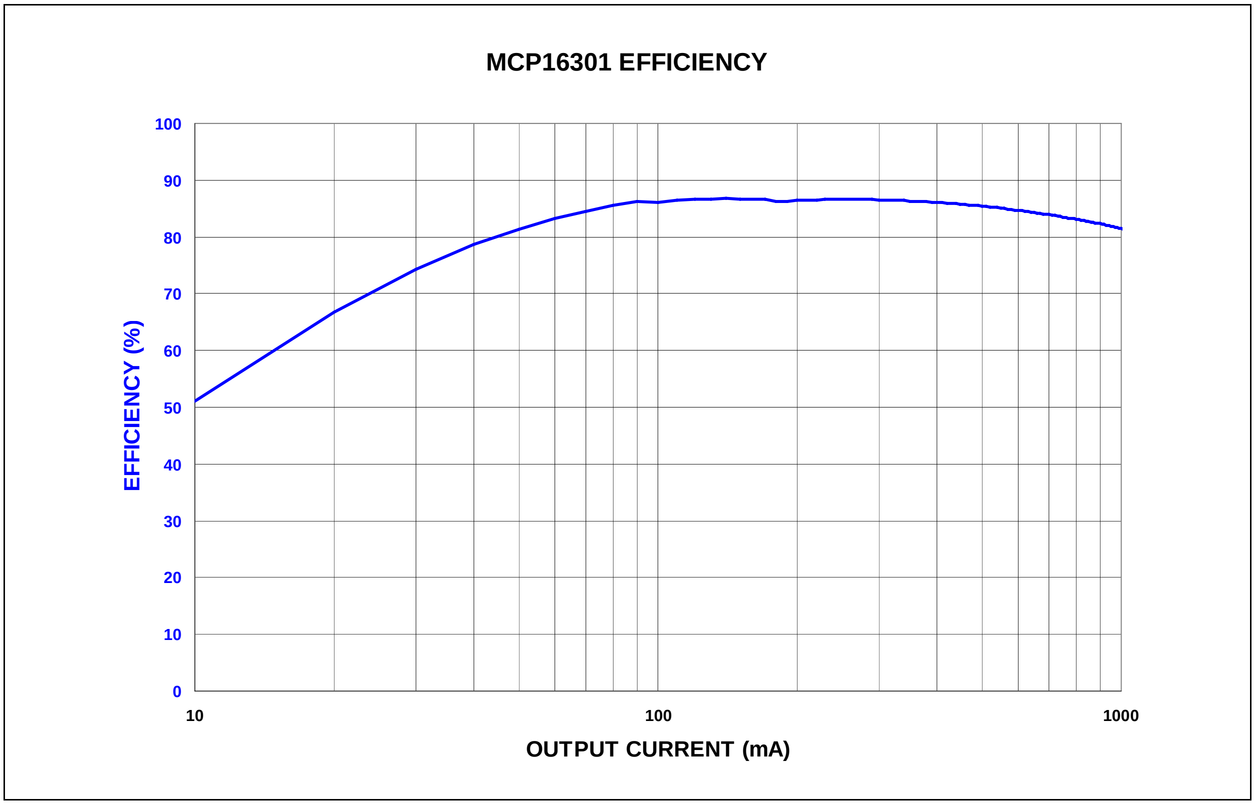

FIGURE 3: *MCP16301 Design Analyzer Efficiency vs Output Current.*

SUMMARY

The MCP16301 Design Analyzer provides the designer with a tool to analyze the dynamic behavior of the MCP16301 Buck Converter. It accurately predicts the dynamic operation, reducing the engineering cost, schedule times, and hones in on an optimized final solution. However, the Design Analyzer should not be considered a substitute for proper in-system verification and validation.

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