Application Report
SLUA672 – January 2013

Using the Improved CCM Small-Signal Model to Predict the Loop Stability of UCC289X Active Clamp Forward Converter

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ABSTRACT

In this paper, the improved small-signal model with peak current mode (PCM) control for the active-clamp forward converter under continuous inductor current condition is used to predict the practical loop stability for the UCC289X application. To verify the validation of the calculation result, with the practical measurement based on the UCC2897 EVM prototype, the UCC2897A simulation model is also established to have the further verification. It is shown that the calculation result based on the improved small-signal model could also have the precise prediction on the practical loop stability measurement.

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1 Introduction

As the reliability evaluation of the power supply has continued to develop, the loop stability test requirement with the specific loop analysis instrument has become the only necessary way currently. However, engineers normally spend much time debugging the loop stability function in practical development process. For example, with the active clamp converter, the loop stability issue is always encountered due to the difficulty of making a good balance between large signal load dynamic and small signal loop stability, especially for the peak current control mode. The MOS voltage stress has the great effect regarding the optimization of large signal load dynamic. To make a good optimization, engineers normally spend much time doing repeated loop stability debugging.

Although there is dispute that the calculation is not to be applied to the practical measurement due to its inaccurate small-signal model, this may be resolved if the accurate small-signal model can be determined.

This paper is designed to establish such a calculation platform to verify the loop stability based on the improved CCM small-signal model for the active-clamp forward converter used in UCC289X applications. The practical EVM verification example is shown in Figure 1, and much comparison data are provided in this paper. Finally, it is proved that the loop stability calculation is highly useful for the practical design and debugging during development if the UCC289X application is used.

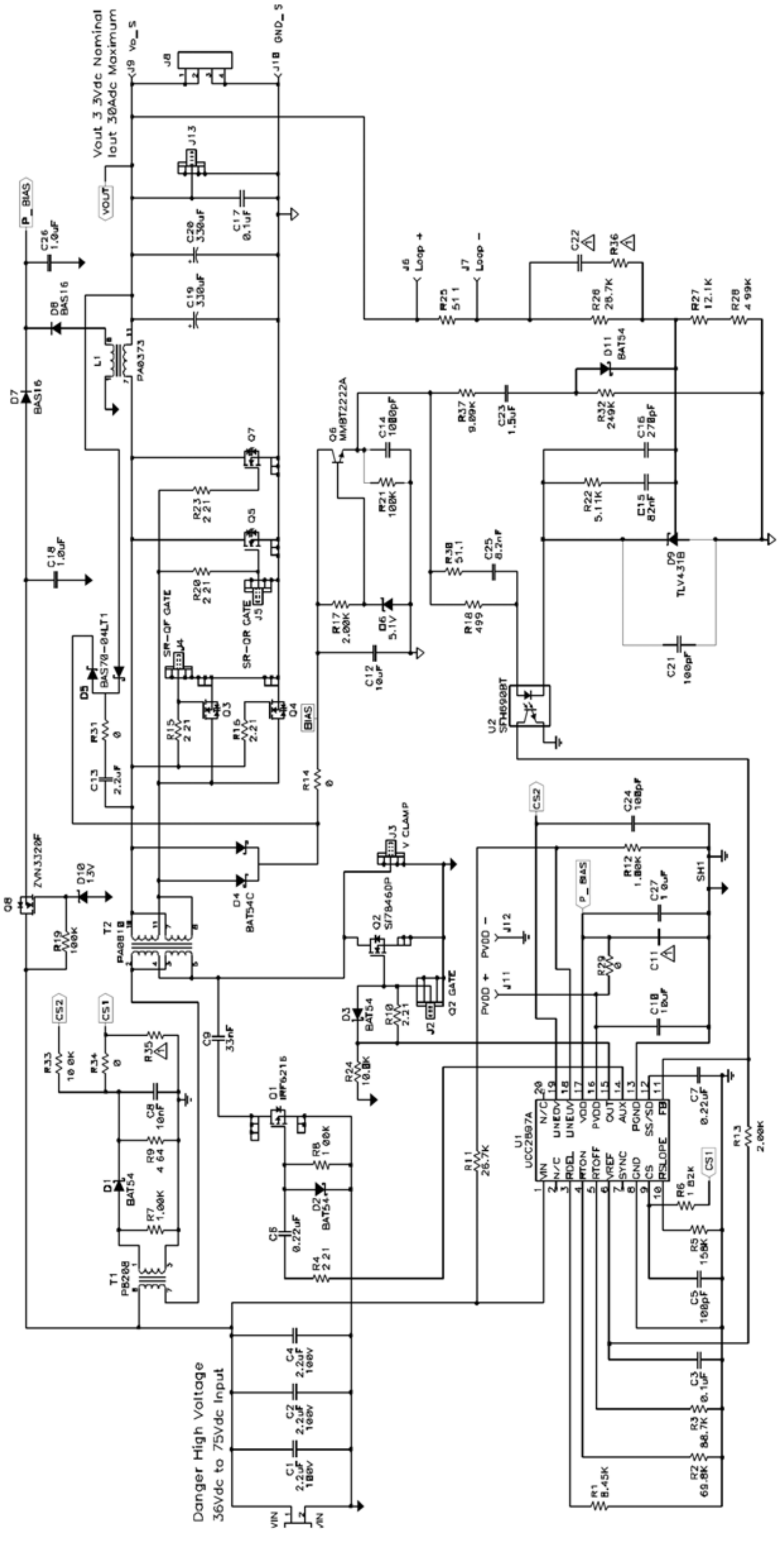
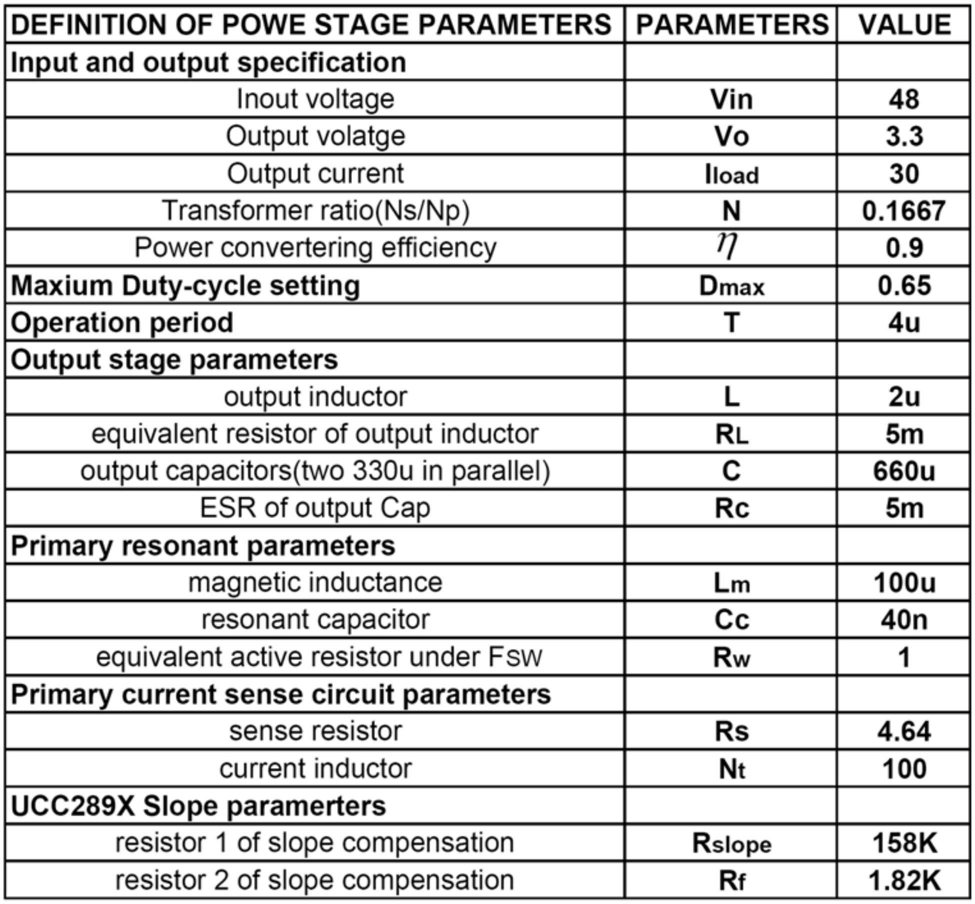


Figure 1. Schematic Based on the EVM

2 Power Stage Transfer Function Calculation

Refer to the BOM of the schematic shown in Figure 1. The power stage parameters are listed in the following table.



DEFINITION OF POWE STAGE PARAMETERS	PARAMETERS	VALUE
Input and output specification		
Inout voltage	**Vin**	**48**
Output volatge	**Vo**	**3.3**
Output current	**I_{load}**	**30**
Transformer ratio(Ns/Np)	**N**	**0.1667**
Power convertering efficiency	η	**0.9**
Maxium Duty-cycle setting	**D_{max}**	**0.65**
Operation period	**T**	**4u**
Output stage parameters		
output inductor	**L**	**2u**
equivalent resistor of output inductor	**R_L**	**5m**
output capacitors(two 330u in parallel)	**C**	**660u**
ESR of output Cap	**Rc**	**5m**
Primary resonant parameters		
magnetic inductance	**L_m**	**100u**
resonant capacitor	**Cc**	**40n**
equivalent active resistor under FSW	**R_w**	**1**
Primary current sense circuit parameters		
sense resistor	**Rs**	**4.64**
current inductor	**N_t**	**100**
UCC289X Slope paramerters		
resistor 1 of slope compensation	**R_{slope}**	**158K**
resistor 2 of slope compensation	**R_f**	**1.82K**

The operation duty-cycle can be solved as:

$$D = \frac{V_{out}}{V_{in} \cdot N \cdot \eta} \tag{1}$$

The output load can be calculated as:

$$R_o = \frac{V_{out}}{I_{load}} \tag{2}$$

The equivalent primary sense resistor is:

$$R_s = \frac{Rs}{N_t} \tag{3}$$

mc can be solved as the following:

$$Vp = \frac{5 \cdot vs}{D_{\max}} \cdot \frac{R_f}{R_{slope}} \tag{4}$$

$$mc = 1 + Vp \Big/ \left(\frac{(N \cdot V_{in} \cdot \eta - V_{out}) \cdot T \cdot N \cdot R_s}{L} + \frac{V_{in} \cdot R_s \cdot T}{L_m} \right) \tag{5}$$

Given the preceding parameters, the Bode and phase characteristic of this transfer function can be plotted on MathCAD or simulation software

$$H_e(s) = 1 + \frac{s}{\omega_n \cdot Q_z} + \frac{s^2}{\omega_n{}^2} \;, \qquad Q_z = -2/\pi \;,\; \omega_n = \pi/T \tag{6}$$

$$K_r = \frac{R_s \cdot T}{2} \cdot \left(\frac{N}{L} + \frac{1}{N \cdot L_m} \right), \qquad D' = 1 - D \tag{7}$$

$$G_{vd}(s) = \frac{V_o}{D} \cdot \frac{1 + s/\omega_{zc}}{1 + s/Q\omega_0 + s^2/\omega_0{}^2} \;,\; G_{id}(s) = \frac{V_{in} \cdot N \cdot (1 + s/\omega_{zp})}{\left(1 + s/Q\omega_0 + s^2/\omega_0{}^2\right) \cdot R_o} \;,\; Z(s) = L_m \cdot s + \frac{D'^2}{Cc \cdot s} + R_\omega \,, \tag{8}$$

Where:

$$\omega_0 = \frac{1}{\sqrt{LC}} \;,\; Q = \frac{1}{\omega_0 \left[L/R_o + (R_L + R_C)C \right]} \;,\; \omega_{zc} = \frac{1}{R_c C} \;,\; \omega_{zp} = \frac{1}{R_o C}$$

For the UCC289X application, the coefficient K_C is determined by the internal divided resistor; it is set as 0.2, then the ultimate power stage transfer function of control to output transfer function is:

$$G_{vc}(s) = \frac{Z_o(s) \cdot kc}{\left(\frac{mc \cdot R_s \cdot T}{D} \cdot \left(\frac{D' \cdot N}{L} + \frac{1}{N \cdot L_m} \right) + \frac{R_s \cdot H_e(s)}{N \cdot D' \cdot Z(s)} \right) \cdot \frac{V_o}{G_{id}(s)} + R_s \cdot N \cdot H_e(s) - \frac{G_{vd}(s)}{G_{id}(s)} \cdot K_r} \tag{9}$$

Figure 2 shows the calculation result:

$$\mathrm{dBGvc}(f) := 20 \cdot \log(|\mathrm{Gvc}(f)|)$$

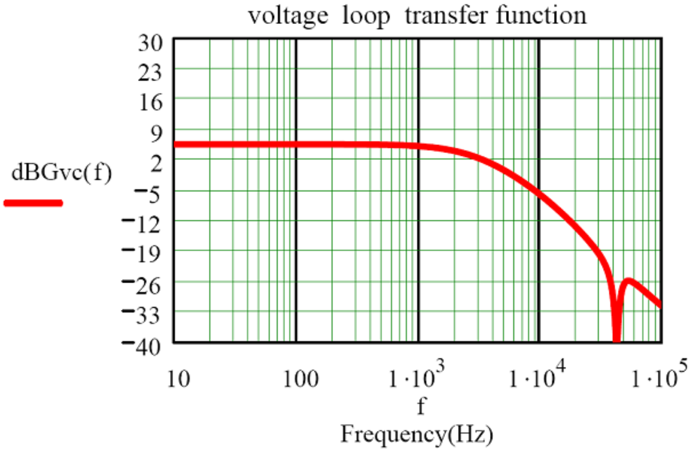


Figure 2. Bode Calculation Regarding the Control to Output Transfer Function

3 Transfer Function for the Feedback Loop

In UCC2897X application, the voltage compensation circuit is mostly used with the circuit shown in Figure 3.

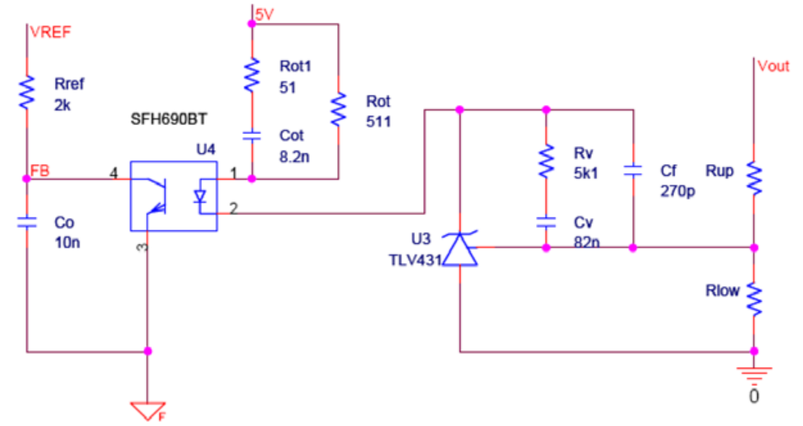


Figure 3. Voltage Compensation Circuit

Modeling an OPTO is paramount for deriving the feedback loop transfer function. Normally, achieving the accurate mode is determined by two parameters. CTR of OPTO, the first parameter, depends on its steady value and can be solved easily. The second parameter is somewhat elusive in most cases because of its high-frequency characteristic.

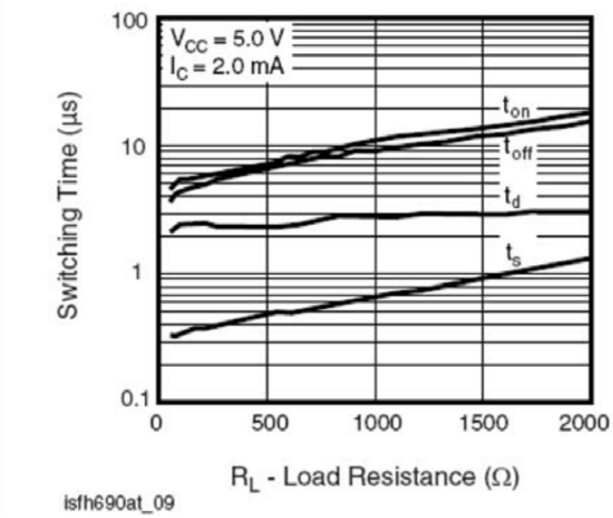


Figure 4. Switching Time versus Load Resistance Regarding SFH690BT

However, the most important thing to affect this high-frequency characteristic is R_L and C_{in}. C_{in} is referred to as the internal capacitance; it is assumed to be added across the output terminals of current control current source for transient analysis. C_{in} is calculated based on the following formula:

$$T_r = 2.2C_{in} \cdot R_L \quad (10)$$

In this application with Ic being 1 mA, it is can be assumed that T_r is about 40u, then C_{in} can be calculated as follows:

$$C_{in} = \frac{40u}{2.2R_L}$$

From the result above, we can choose C_{in} as 10n.

Then the transfer function of feedback is as follows:

$$G_{cv}(s) = \frac{-R_{ref} \cdot CTR}{1 + R_{ref} \cdot C_o \cdot s} \cdot \frac{1 + (R_{ot} + R_{ot1}) \cdot C_{ot} \cdot s}{R_{ot} \cdot (1 + R_{ot1} \cdot C_{ot} \cdot s)} \cdot \frac{1}{R_{up} \cdot (C_v + C_f)} \cdot \frac{1 + R_v \cdot C_v \cdot s}{1 + \frac{R_v \cdot C_v \cdot s}{C_v + C_f}} \quad (11)$$

So, the closed overall transfer function is as follows:

$$G_{total}(s) = G_{cv}(s) \cdot G_{vc}(s) \quad (12)$$

Close the loop with the following functions:

$$dB(G_{cv}(s)) = 20 \cdot \log|G_{cv}(s)| \qquad dB(G_{total}(s)) = 20 \cdot \log|G_{cv}(s) \cdot G_{vc}(s)|$$

$$Ph(G_{cv}(s)) = \arg(dB(G_{cv}(s)) \cdot \Phi) \qquad Ph(G_{total}(s)) = \arg(dB(G_{cv}(s) \cdot G_{vc}(s)) \cdot \Phi)$$

The plotted result using MathCAD is as follows:

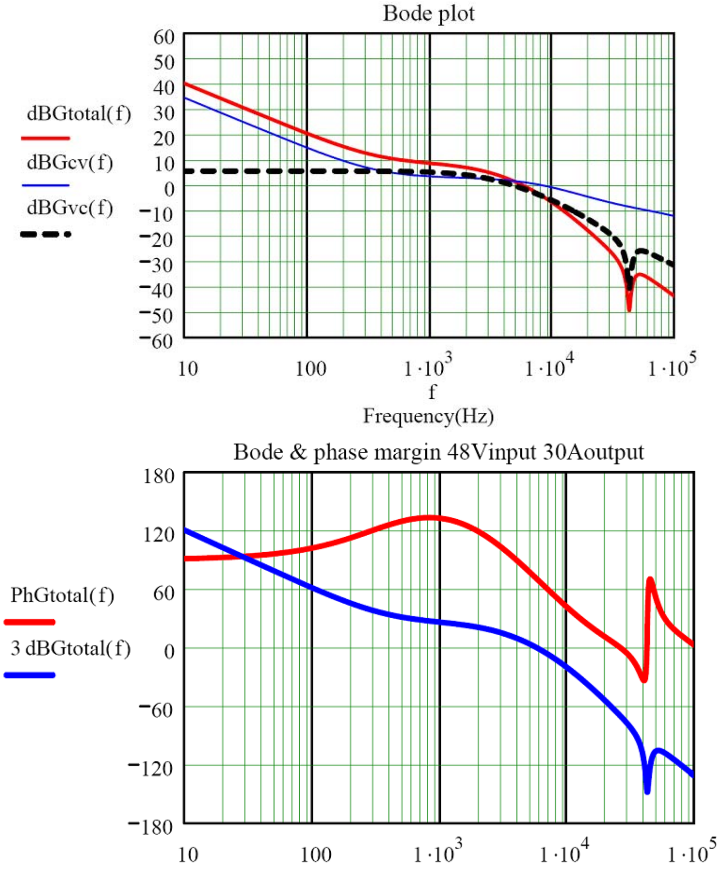


Figure 5. Overall Voltage Loop Stability Calculation Result With the Loop Closed

4 Loop Stability Verification Through Simulation

To demonstrate the validation of the transfer function presented above, a UCC2897A simulation model is built to create the typical circuit based on the EVM application scheme. The circuit parameters are basically coincident with those proposed in the EVM BOM.

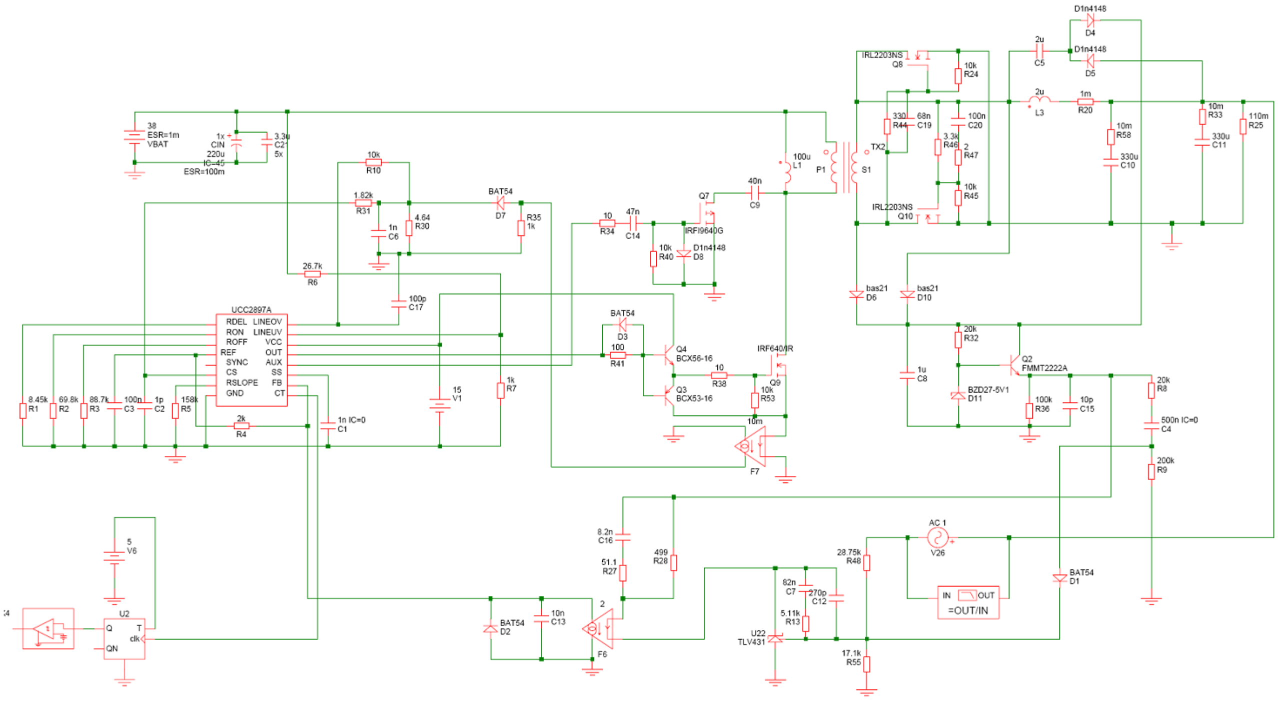


Figure 6. Simulation Circuit for the Loop Stability Verification

Figure 7 through Figure 9 present the comparison between calculation and simulation.

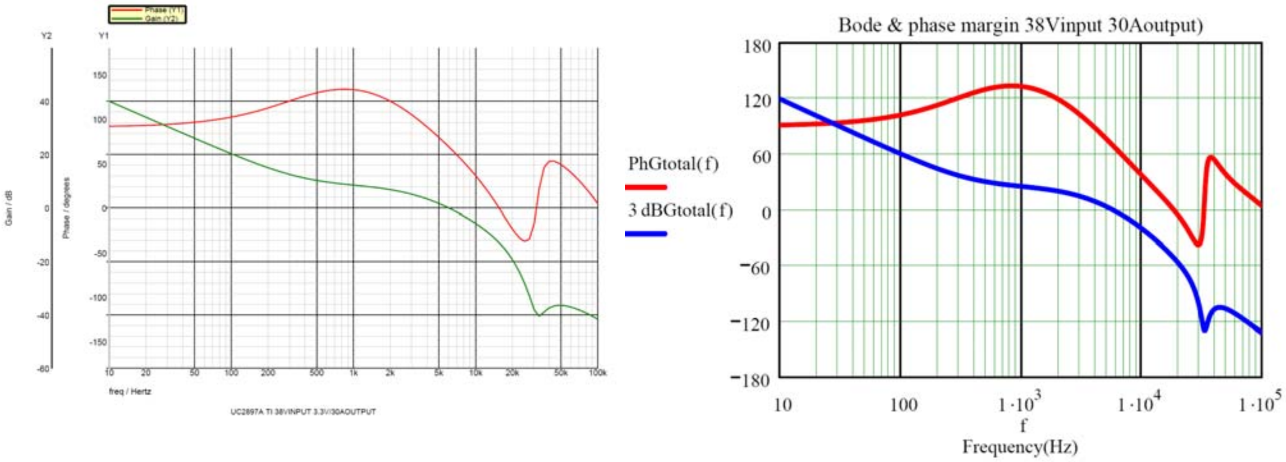


Figure 7. Overall Voltage Loop Plot Comparison Between Calculation and Measurement Under 38-Vdc Input and 3.3-V/30-A Output Operation

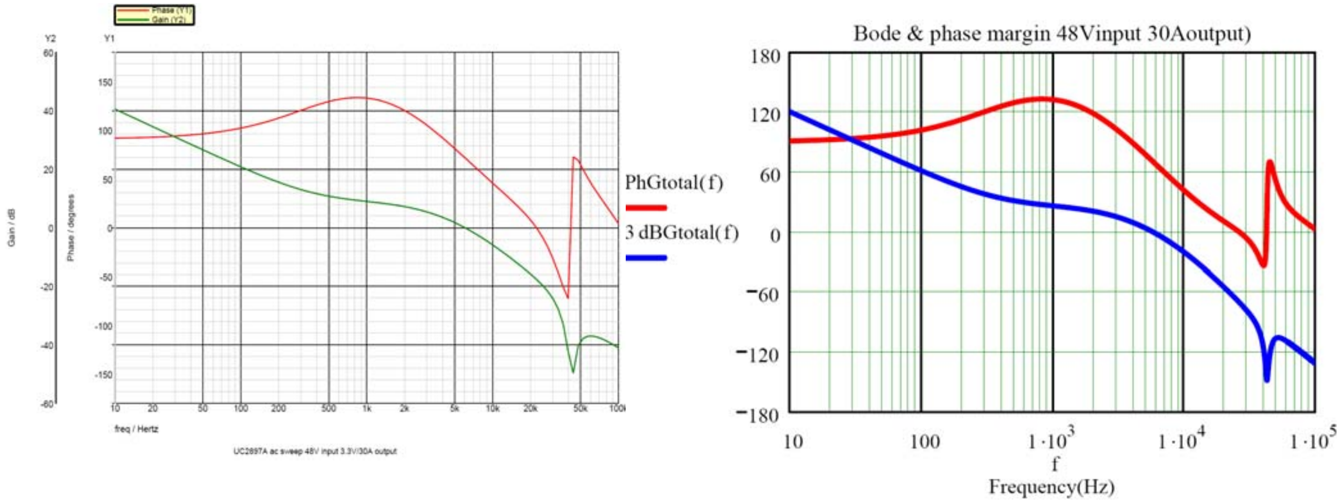


Figure 8. Overall Voltage Loop Plot Comparison Between Calculation and Measurement Under 48-Vdc Input and 3.3-V/30-A Output Operation

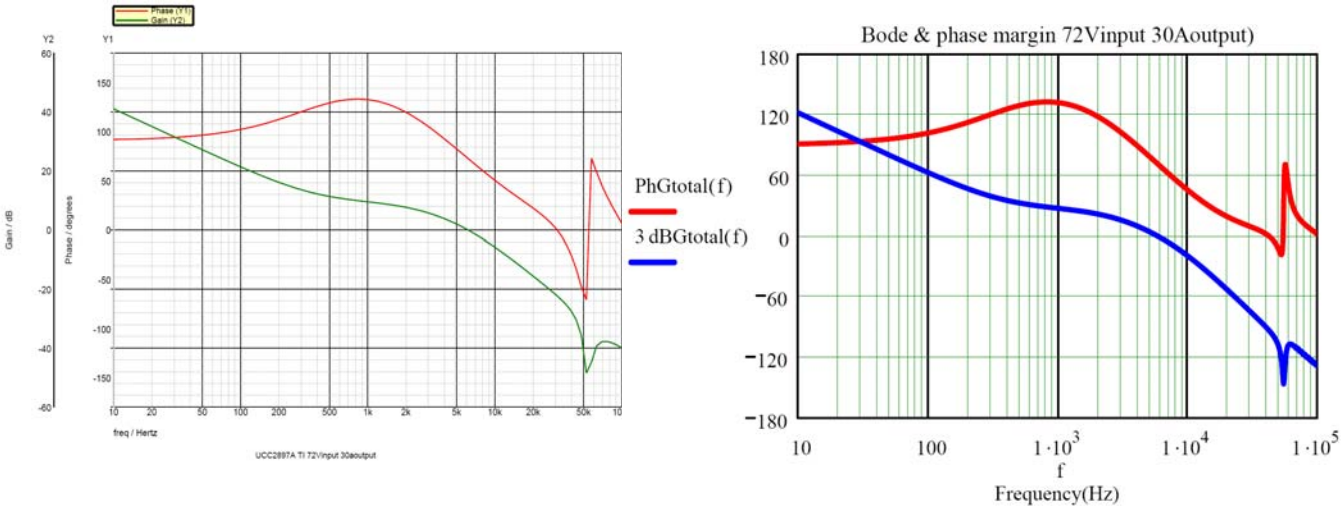


Figure 9. Overall Voltage Loop Plot Comparison Between Calculation and Measurement Under 72-Vdc Input and 3.3-V/30-A Output Operation

The following table shows the comparisons:

Comparison Items	Calculation/Simulation	Calculation/Simulation	Calculation/Simulation
Input and Output Specification	**Cross-Frequency**	**Phase Margin (Degree)**	**Gain Margin (-dB)**
38Vdc input/3.3V@30A	5.2K/6K	72/70	45/30
48Vdc input/3.3V@30A	5.5K/6K	71/70	60/55
72Vdc input/3.3V@30A	6.5K/6K	70/70	90/70

It is shown that the calculation results match well with the simulation result.

5 Loop Stability Verification Through Practical Measurement

To have the further verification for the calculated loop plot, the calculation result is compared with the practical measurement based on the UCC2891EVM when 48-Vdc input and 75Vdc input:

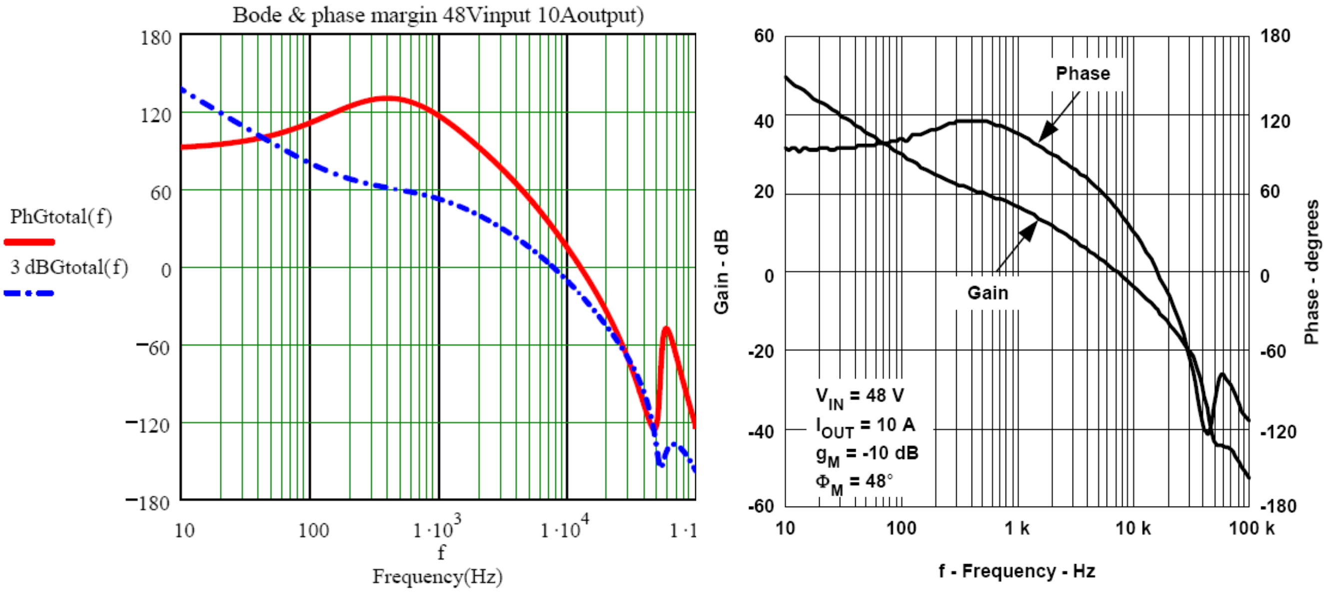


Figure 10. Overall Voltage Loop Plot Comparison Between Calculation and Measurement Under 48-Vdc Input and 3.3-V/10-A Output Operation

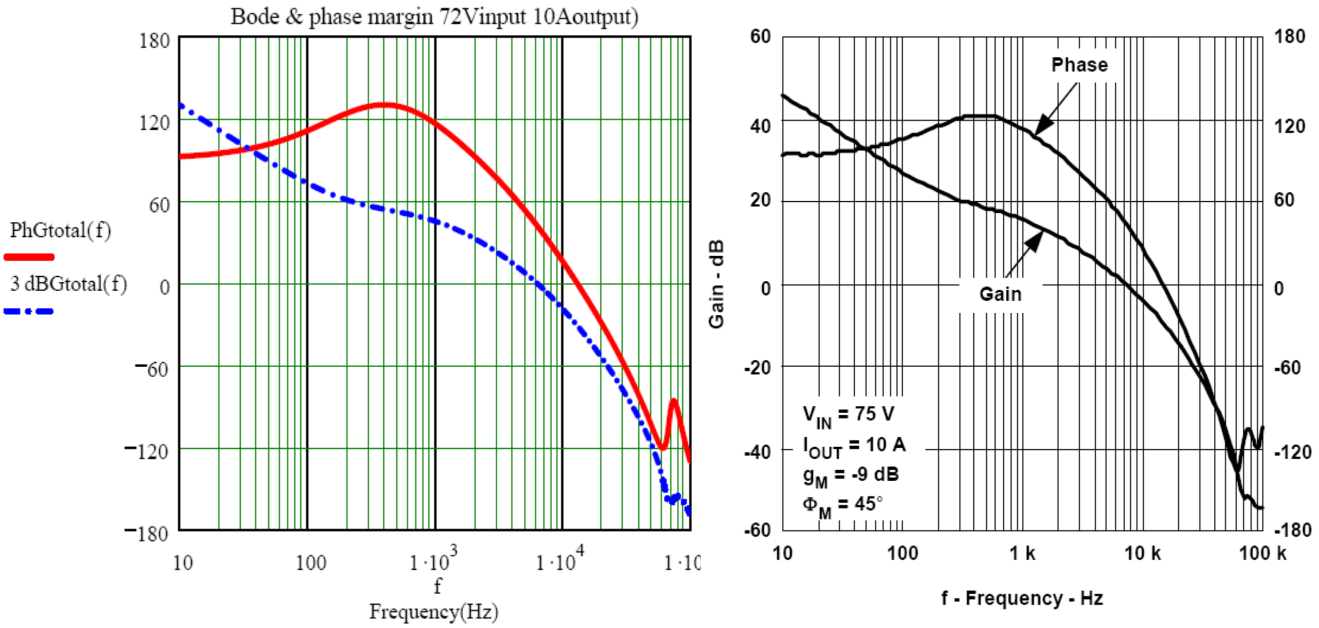


Figure 11. Overall Voltage Loop Plot Comparison Between Calculation and Measurement Under 75-Vdc Input and 3.3-V/10-A Output Operation

The following table shows the comparisons:

Comparison Items	Calculation/Measured	Calculation/Measured	Calculation/Measured
Input and Output Specification	**Cross-Frequency**	**Phase Margin (Degree)**	**Gain Margin (-dB)**
48Vdc input/3.3V@10A	7K/6K	42/48	15/10
75Vdc input/3.3V@10A	6K/7K	40/45	25/9

It is shown that the calculation results match well with the measured result.

NOTE: The calculation gain margin has been a little far with the measured results due to the highly complicated prediction regarding the resonant parasitic parameters when frequency is so high.

6 Conclusions

Using the improved small-signal model regarding the UCC289X active-clamp forward converter to predict the actual loop stability is helpful for practical loop debugging work. This practice will be more efficient for the engineers to debug the loop stability.

7 References

1. *UCC289/1/2/3/4 Current-Mode Active Clamp PWM Controller*, datasheet (SLUS542)
2. *UCC2897A Current-Mode Active Clamp PWM Controller*, datasheet (SLUS829D)
3. *UCC3580/-1/-2/-3/-4 Single Ended Active Clamp Reset PWM*, datasheet, (SLUS292A)
4. Steve Mappus, *UCC2891EVM, 48-V to 1.3-V, 30-A Forward Converter with Active Clamp Reset, User's Guide to Accommodate UCC2891EVM*, (SLUU178)
5. *Understanding and Designing an Active Clamp Current Mode Controlled Converter Using the UCC2897A* (SLUA 535)
6. An improved CCM small signal model with PCM control applied for UCC284X/UCC289X/LM5026,

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