TI-PMLK

TI Power Management Lab Kit
Buck-Boost Experiment Book

Texas Instruments

SSQU009A
PMLKBUCKBOOSTEVM REV A

Texas Instruments

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Many people have collaborated with me in the realization of the TI-PMLK project, in different times, at different levels, in different ways. My sincerest thanks go to the Texas Instruments University Program Team and to the University of Salerno Power Electronics Laboratory Team.

Nicola Femia

Preface

Felix, qui potuit rerum cognoscere causas...
(Happy, he who could capture the origins of things...)
Publio Virgilio Marone, Mantova 70 B.C. – Brindisi 19 B.C.

Design is an exciting and fascinating art. Power electronics, for its interdisciplinarily nature, is a challenging field where the knowledge of *why* makes all the difference in understanding *how* to achieve design goals. The *will of learning* and the *means for learning* are the two basic ingredients needed to develop the virtuous ability to understand the reality of problems, to select the appropriate techniques and methods to solve them, to make meaningful design decisions and to intelligently evaluate the solutions.

The main purpose of the TI-PMLK collection of Experiment Books is to stimulate the spirit of investigation in students and practicing engineers who are engaged in learning and understanding the design of power supplies. The experiments cover a basic anthology of topics and issues encountered in the design of low power dc-dc non-isolated power supplies, such as power supplies topologies and characteristics, modes of operation, efficiency, control, stability, accuracy, transient response, noise, power magnetics, and more. The experiments can be performed by using the power supply boards of the TI-PMLK suite, which includes low dropout linear regulators and Buck, boost and Buck-Boost switching regulators. The Experiment books are not intended to provide an exhaustive overview of design issues or definitive design hints: rather, it is meant to guide the reader into a multifaceted active learning experience.

All the experiments are based on a logical sequence of steps. They start with the *Case Study* section, which provides the description of the specific property or feature relevant to the power supply board to be used in the experiment, and illustrates the goal and the type of measurement to be done. The *Theory Background* section provides a short summary of concepts, models and equations, supporting the interpretation and understanding of the incoming experimental observations. The *Measurement Setup* section provides the instructions for connecting the instruments needed for the experiments to the board under test. Warnings are provided to prevent main mistakes. The *Test* section provides instructions on how to execute the measurements, and guidelines on how to analyze and understand the results of the measurements. Each test includes an *Answer* section, where the user is required to answer questions and to provide a discussion about the behavior of the board under test, relevant to the specific performance under investigation, based on the observation of the measurements results and on the application of concepts and properties illustrated through the various sections of the experiment. The *Discussion* section provides comments to achieve a better understanding of conceptual and practical correlations among system characteristics and operating performance. The final *Experimental Plots* section illustrates and discusses the results of some sample measurements.

Preface (cont.)

The experiments cover a variety of steady-state, transient and dynamic tests. The tests are mostly based on time domain measurements, while some tests focus on the investigation of dynamic properties that are described through frequency response functions, such as the power supply rejection ratio. This allows a user to conduct a complete experience on the characterization and understanding of power supply issues. Most of the experiments require basic laboratory equipment, including a power supply, some multi-meters, an oscilloscope and a load. Some tests require more sophisticated instrumentation, such as a dynamic source, a dynamic load, and a vector network analyzer, for best measurement.

The boards have been designed to allow the investigation of the influence of physical parameters and operating conditions of a power supply on its own performances. Various combinations of power and control components can be selected. Most of them yield operating conditions that fit good engineering standards. Other ones may lead to operating conditions typically undesired in industry applications, such as instability. Thus, the reader can achieve a sound understanding of such real phenomena.

Suggested combinations of power and control parts are provided for each experiment. The user is invited in some experiments to detect combinations that yield a certain operating condition or behavior. The user can select the setup of jumpers and connectors to generate a great variety of conditions. The book provides recommendations and warnings for safe board operation and for effective measurements. Before performing any experiment, the reader is strongly recommended to read carefully all the warnings and the introductory section of the book, where the specific description of the board is provided and information on settings and performance are given, including forbidden combinations and special operating conditions. The reader is also strongly invited to read the manufacturers' datasheets of all the parts mounted in the boards, especially the control chips, to improve the knowledge and the understanding of each device.

A good knowledge of the power supplies implemented on the boards, supported by the heuristic observations and the models and methods discussed in the book, help the user to distinguish what can be done from what cannot be done.

The level of detail and completeness of models discussed in the *Theory Background* section vary from experiment to experiment. Sometimes the models include certain specific properties, other times they are simplified or approximated. Achieving familiarity with models is a fundamental learning step: a good power supply designer has to be able to grade the importance of modeling certain properties, at device level as well as at system level, in order to assess if they really provide meaningful and influential information to meet the application requirements. Essential formulas and expressions for the basic analysis of the phenomenon under investigation are mostly introduced without step-by-step theoretical derivations, which are beyond the objectives of the book.

The reader is encouraged to test him(her)self in filling this gap, through an in-depth study of models and methods for the analysis and design of power supplies discussed in the cited references.

Preface (cont.)

The parameters of semiconductor and passive power components mounted on the boards are provided in the book to allow the application of analysis formulas and design equations. All parameters of power components are affected by uncertainty, due to tolerances, ageing and influence factors like temperature, current, voltage and frequency. The values collected in the books have been extracted from the manufacturers' datasheets in certain reference conditions. The power and control components and sub-circuits of integrated circuits controlling the power supplies, which determine modes of operation and performances, are subjected to the influence of temperature, voltage, current and frequency too. As a consequence, the predictions of formulas and equations provided in the book, based on the parameters of power and control devices, can show different levels of agreement with respect to the results of experimental measurements.

The user is strongly encouraged to read the references provided in the book, to analyze the characteristics and the behavior of integrated circuits and power components of the boards, and to verify if different values of the parameters of components can be used to achieve a better compliance between the results of formulas and the results of experimental measurements. The investigation of real device characteristics and of their influence on overall performance of a power supply is a fundamental component of designers' work.

The ultimate intention of this book is to accompany the reader through an active experience, made of observations, application of physics and mathematics, reality investigation and system level reasoning. That is engineering insight. The Author hopes the reader may fully enjoy this book and the pleasure of being a design engineer, a creative and autonomous thinker, able to acquire and re-elaborate the knowledge to win ever new design challenges.

Know why, know how!

Nicola Femia

Nicola Femia is Professor at the University of Salerno, Italy, where he teaches Power Electronics and Energetic Intelligence, in the Electronic Engineering and Computer Engineering Master Degree Programs. He leads the Power Electronics and Renewable Sources Laboratory. Over the past 25 years, he has promoted and directed worldwide university and industry research activities and education programs on power electronics, photovoltaic systems, and power design. He has been Visiting Professor at the Electrical Engineering Department of the Stanford University, Stanford, CA, where he taught Power Electronics Control and Energy Aware Design.

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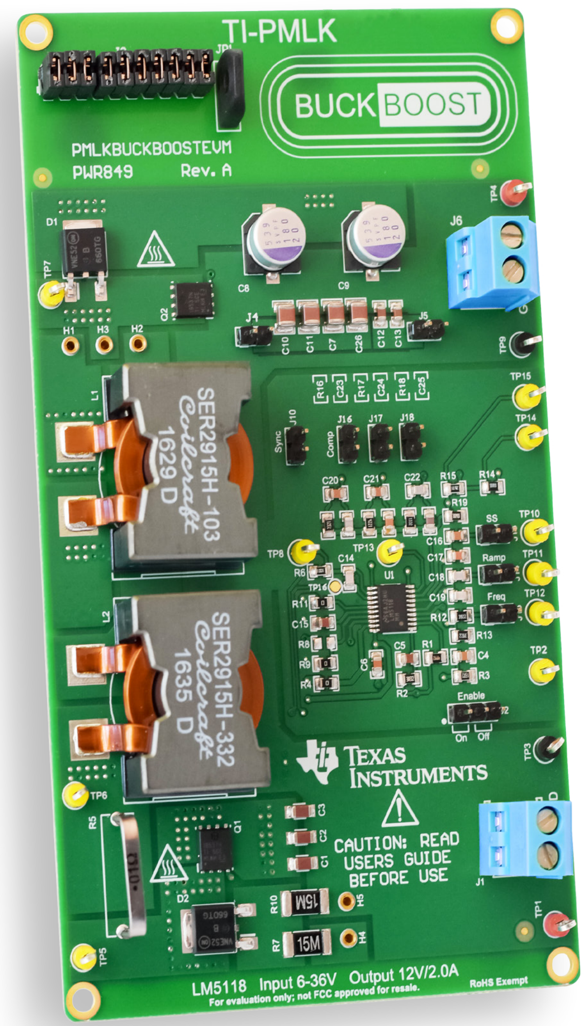
Instrumentation needed for experiments

The instrumentation recommended for the execution of the experiments of this book is comprised of:

- *DC power supply 50V/20A*
- *DC electronic load 20V/10A with dynamic current mode capability*
- *digital multimeter with 4½ digit resolution*
- *250MHz 4-channels Digital Oscilloscope + 2 current probes 20A/50MHz*
- *10MHz Waveform Generator*
- *series of 10Ω, 15Ω and 22Ω power resistors with 50W power rating*

The instrumentation used in the lab tests corresponding to the Experimental Plot samples shown in the book is comprised of:

- *TTi QPX1200S Power Supply 60V/50A*
- *Sorensen Electronic Load SLM-4 mainframe + SLM series electronic load modules 60V/60A*
- *Hewlett-Packard 34401A multimeter*
- *LeCroy WaveRunner 44Xi 400MHz 4-channels Digital Oscilloscope, with 2 Tektronix TCP 305 50A current probe and 2 Tektronix TCP A300 amplifier*
- *Agilent 33500B 10MHz Waveform Generator*
- *ARCOL 50W 10Ω, 15Ω , 22Ω power resistors*



TI-PMLK Buck-Boost

The TI-PMLK-BUCK-BOOST is an experimental power supply board based on the wide voltage range emulated current-mode controller LM5118

TI-PMLK LM5118 Schematic

The TI-PMLK Buck-Boost LM5118 board accepts input voltages in between 6V and 36V, while regulating the output voltage at 12V with maximum load current of 2A.

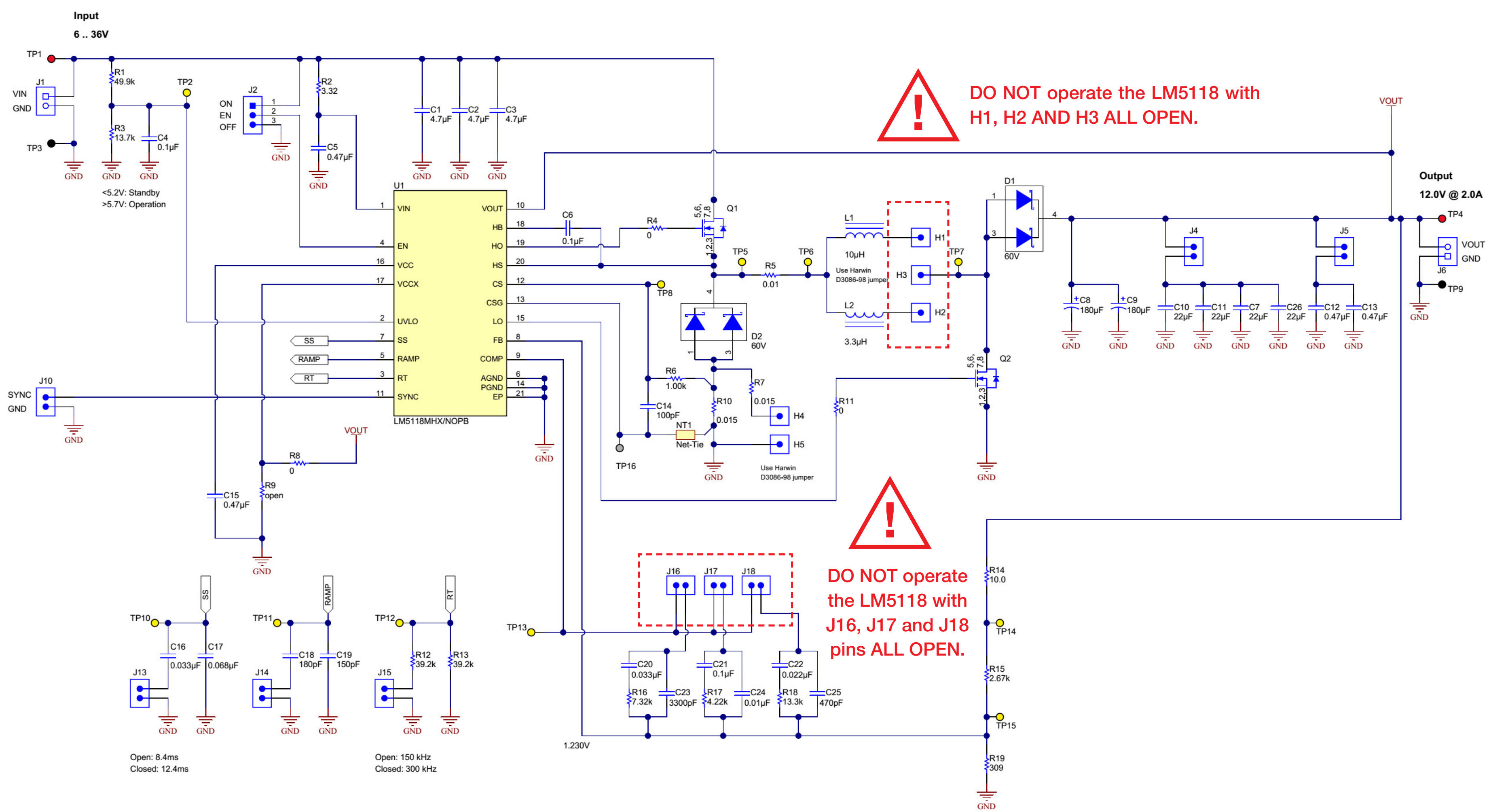


Figure 1. Circuit schematic of TI-PMLK LM5118 Buck-Boost regulator

TI-PMLK LM5118 Bill of Materials

Designator	Description	Manufacturer	Part Number
C_1, C_2, C_3	4.7µF Ceramic Capacitor, 50 V, +/- 10%, X7R, 1206	Taiyo Yuden	UMK316AB7475KL-T
C_4, C_6, C_{21}	0.1µF Ceramic Capacitor, 50V, +/-10%, X7R, 0805	Kemet	C0805C104K5RACTU
C_5, C_{12}, C_{13}, C_{15}	0.47µF Ceramic Capicitor, 50 V, +/- 10%, X7R, 0805	Taiyo Yuden	UMK212B7474KG-T
C_7, C_{10}, C_{11}, C_{26}	22µF Ceramic Capacitor, 25 V, +/- 10%, X7R, 1210	MuRata	GRM32ER71E226KE15L
C_8, C_9	180µF Aluminum Polymer Capacitor, 20 V, +/- 20%, 25mΩ, 8.0x7.0mm SMD	Panasonic	20SVPF180M
C_{14}	100pF Ceramic Capacitor, 50V, +/-5%, C0G/NP0, 0805	MuRata	GQM2195C1H101JB01D
C_{16}, C_{20}	0.033µF Ceramic Capacitor, 50V, +/-10%, X7R, 0805	MuRata	GRM219R71H333KA01D
C_{17}	0.068µF Ceramic Capacitor, 50V, +/-10%, X7R, 0805	MuRata	GRM21BR71H683KA01L
C_{18}	180pF Ceramic Capacitor, 50 V, +/- 5%, C0G/NP0, 0805	Yageo America	CC0805JRNP09BN181
C_{19}	150pF Ceramic Capacitor, 50V, +/-5%, C0G/NP0, 0805	MuRata	GRM2165C1H151JA01D
C_{22}	0.022µF Ceramic Capacitor, 50V, +/-10%, X7R, 0805	MuRata	GRM216R71H223KA01D
C_{23}	3300pF Ceramic Capacitor, 50V, +/-5%, C0G/NP0, 0805	MuRata	GRM2165C1H332JA01D
C_{24}	0.01µF Ceramic Capacitor, 50V, +/-10%, X7R, 0805	MuRata	GRM216R71H103KA01D
C_{25}	470pF Ceramic Capacitor, 50V, +/-5%, C0G/NP0, 0805	MuRata	GRM2165C1H471JA01D
D_1, D_2	Schottky Diode, 60V, 6A, DPAK	ON Semiconductor	MBRD660CTT4G
L_1	10µH Inductor, Shielded E Core, Ferrite, 23.4A, 1.86mΩ, SMD	Coilcraft	SER2915H-103KL
L_2	3.3µH Inductor, Shielded E Core, Ferrite, 30A, 1.86mΩ, SMD	Coilcraft	SER2915H-332KL
Q_1, Q_2	MOSFET, N-CH, 60V, 50A, SON 5x6mm	Texas Instruments	CSD18537NQ5A
R_1	49.9kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW080549K9FKEA
R_2	3.32Ω Resistor, 1%, 0.125 W, 0805	Yageo America	RC0805FR-073R32L
R_3	13.7kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW080513K7FKEA
R_4, R_8, R_{11}	0Ω Resistor, 5%, 0.125W, 0805	Vishay-Dale	CRCW08050000Z0EA
R_5	0.01Ω Resistor, 1%, 3W, TH	TT Electronics/IRC	OAR3R010FLF
R_6	1kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW08051K00FKEA
R_7, R_{10}	0.015Ω Resistor, 1%, 1 W, 2512	Panasonic	ERJ-M1WSF15MU
R_9	0Ω Resistor, OPEN, 5%, 0.125W, 0805	Vishay-Dale	CRCW08050000Z0EA
R_{12}, R_{13}	39.2kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW080539K2FKEA
R_{14}	10Ω Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW080510R0FKEA
R_{15}	2.67kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW08052K67FKEA
R_{16}	7.32kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW08057K32FKEA
R_{17}	4.22kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW08054K22FKEA
R_{18}	13.3kΩ Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW080513K3FKEA
R_{19}	309Ω Resistor, 1%, 0.125W, 0805	Vishay-Dale	CRCW0805309RFKEA
U_1	LM5118: 2-75V Wide Vin, Current Mode Non-synchronous Buck-Boost Controller	Texas Instruments	LM5118MHX/NOPB

(use the part numbers of components to retrieve, through the manufacturers websites listed in the references, details about parameters and data that are used in the formulae provided for calculations in each experiment)

TI-PMLK LM5118 Board

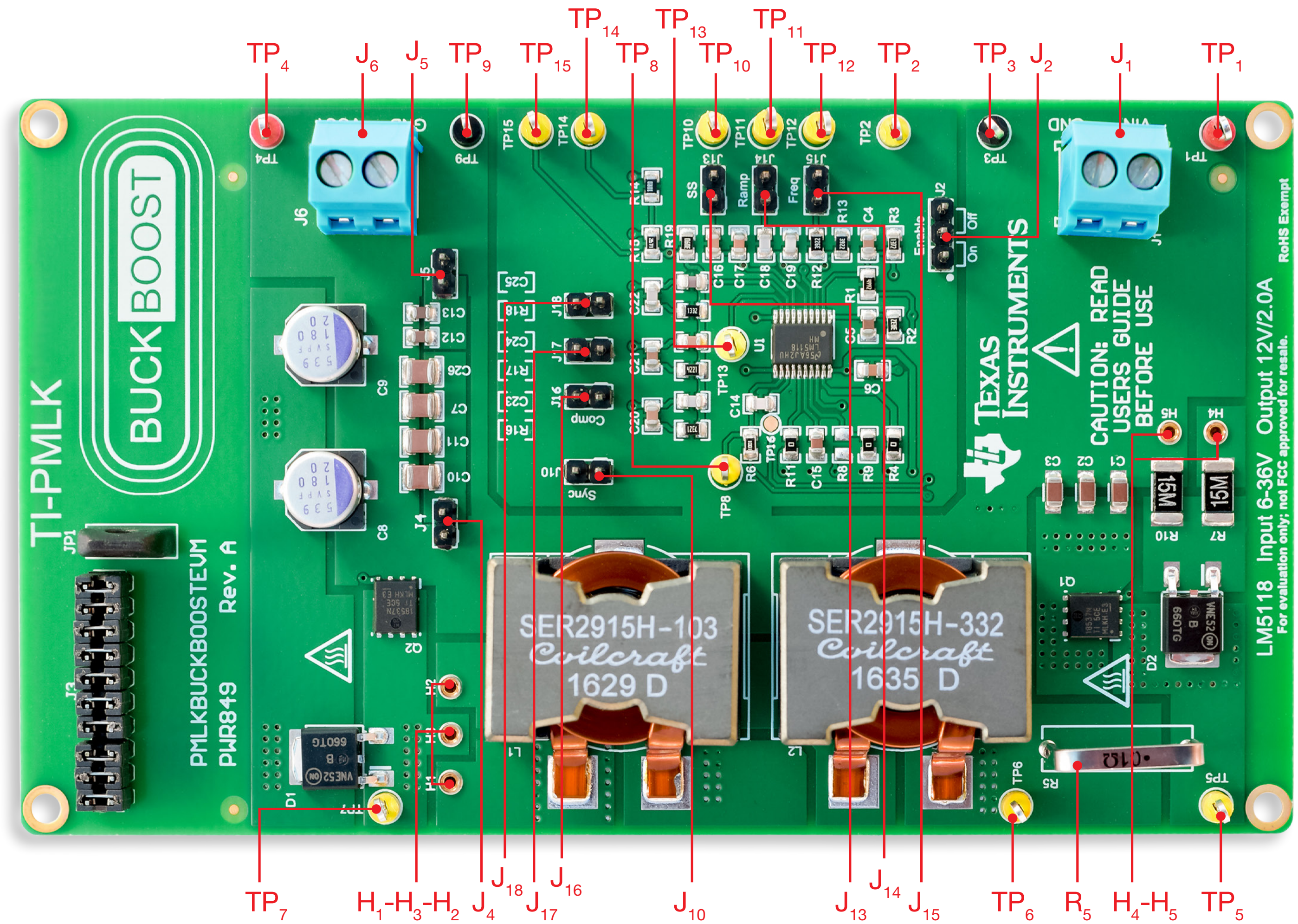


Figure 2. Plain view of TI-PMLK LM5118 BUCK-BOOST regulator board

TI-PMLK LM5118 Connectors, Jumpers and Test Pins

Descriptors and functions for Connectors, Jumpers and Test Pins

Connectors

J_6 - output voltage
J_1 - input voltage

Jumpers

J_2 - connects the enable pin to positive pole of input voltage (enabled) or to ground (disabled)
J_4 - connects C_7, C_{10}, C_{11}, C_{26} (4x22µF) output capacitors
J_5 - connects C_{12}, C_{13} (2x0.47µF) output capacitors
J_{10} - connects to external synchronization signal
J_{13} - soft-start setup:
open → shorter soft-start time (about 8.4ms)
shorted→ longer soft-start time (about 12.4ms)
J_{14} - compensation ramp slope setup:
open → higher slope, shorted → lower slope
J_{15} - switching frequency setup:
open →f_s=150kHz, shorted → f_s=300kHz
J_{16} - error amplifier gain setup: connects parts R_{16}, C_{20}, C_{23} (lower cross-over frequency with L=10µH)
J_{17} - error amplifier gain setup: connects parts R_{17}, C_{21}, C_{24} (lower cross-over frequency with L=3.3µH)
J_{18} - error amplifier gain setup: connects parts R_{18}, C_{22}, C_{25} (higher cross-over frequency with L=10µH)

High current jumpers

H_1-H_3 - connects inductor L_1 (ferrite core, 10µH)
H_2-H_3 - connects inductor L_2 (ferrite core, 3.3µH)
H_4-H_5 - inductor current sensing resistance setup:
open → R_{sns}=15mΩ, shorted → R_{sns}=7.5mΩ

Test pins

TP_1 - positive pole of input voltage
TP_3 - ground pole of input voltage
TP_4 - positive pole of output voltage
TP_9 - ground pole of output voltage
TP_2 - under voltage lock out signal
TP_5 - input side switching node, can used together with TP_6 to sense the voltage across the current shunt R_5. The shunt resistor R_5 allows to hang a current probe for inductor current measurement.
TP_6 - can be used together with TP_7 to sense the inductor voltage, and together with TP_5 to sense the voltage across the current shunt R_5
TP_7 - output side switching node, can be used together with TP_6 to sense the inductor voltage
TP_8 - current sensing signal
TP_{10} - soft-start signal
TP_{11} - compensation ramp signal
TP_{12} - PWM ramp signal
TP_{13} - control signal
TP_{14} - connection pin for loop gain measurements, can be used together with TP_4 to inject the ac stimulus into the 10Ω resistor R_{14}
TP_{15} - feedback control signal

Voltage and Current Measurements

- hang a current probe to the shunt resistor R_5 to measure the inductor current
- use TP_1 and TP_3 to measure the input voltage
- use TP_4 and TP_9 to measure the output voltage
- use TP_5 and TP_3 to measure the input side switching node voltage
- use TP_7 and TP_9 to measure the output side switching node voltage
- use TP_{13} and TP_9 to measure the feedback signal
- hang a current probe to one of the external power wires connected to J_3 to measure the input current
- hang a current probe to one of the external power wires connected to J_4 to measure the load current

Notes, Warnings and Recommendations

NOTES

- The compensation set with J_{16} shorted, J_{17} open and J_{18} open is tailored to achieve about 52° phase margin at 2kHz cross-over frequency with inductance L=10uH (H_1-H_3 shorted), current sensing gain A_s=150mΩ (H_4-H_5 open) and ramp capacitance C_{ramp}=330pF (J_{14} shorted), at minimum input voltage and maximum load current
- The compensation set with J_{18} shorted, J_{17} open and J_{16} open is tailored to achieve about 52° phase margin at 4kHz cross-over frequency with inductance L=10uH (H_1-H_3 shorted), current sensing gain A_s=150mΩ (H_4-H_5 open) and ramp capacitance C_{ramp}=330pF (J_{14} shorted), at minimum input voltage and maximum load current
- The compensation set with J_{17} shorted, J_{16} open and J_{18} open is tailored to achieve about 52° phase margin at 1kHz cross-over frequency with inductance L=3.3uH (H_2-H_3 shorted), current sensing gain A_s=150mΩ (H_4-H_5 open) and ramp capacitance C_{ramp}=150pF (J_{14} open), at minimum input voltage and maximum load current

WARNINGS AND RECOMMENDATIONS

1) **DO NOT** exceed input and output voltage and current ratings

2) If the board is terminated in the output onto an electronic load in constant current mode, the sequence to follow is:
   a) at the turn on: turn on the input power supply then turn on the load
   b) at the turn off: turn off the load then turn off the input power supply

3) Whatever change in the setup of jumpers has to be done, the board has to be shut down first.

4) **DO NOT** operate the regulator with J_{16} **AND** J_{17} **AND** J_{18} **ALL OPEN**.

5) **DO NOT** operate the regulator with J_{16} **AND** J_{17} **AND** J_{18} **ALL SHORTED**.

6) **DO NOT** operate the regulator with J_{16} **AND** J_{17} **SHORTED**.

7) **DO NOT** operate the regulator with J_{16} **AND** J_{18} **SHORTED**.

8) **DO NOT** operate the regulator with J_{17} **AND** J_{18} **SHORTED**.

9) **DO NOT** operate the regulator with both H_1-H_3 **AND** H_2-H_3 **OPEN**.

Experiment 1

The goal of this experiment is to analyze the impact of input voltage, load current and inductance on the continuous/discontinuous operation mode and on the duty cycle of the Buck-Boost converter.

Case Study

The goal of this experiment is to analyze the impact of the input voltage, the load current and the inductance on the continuous/discontinuous operation of the Buck-Boost converter, and also to analyze how the duty-cycle changes depending on the operating conditions in the two operation modes.

The TI-PMLK LM5118 Buck-Boost regulator operates with V_{in}=[6,36]V[(1)], while regulating the output voltage at the nominal value V_{out}=12V in the load current range I_{out}=[0,2]A. Fig.1 shows the simplified circuit schematic of the regulator. The LM5118 Buck-Boost regulator is based on a two-switches two-diodes topology, which allows to achieve non inverting step-up and step-down voltage conversion. The LM5118 controller senses the input voltage and drives the switches so that the converter operates in **Buck Mode (BM)** when V_{in}>15.4V, by switching the MOSFET Q_1 and the diode D_1, while the MOSFET Q_2 and the diode D_2 are permanently OFF and ON, respectively. When V_{in}<13.2V the converter operates in **Buck-Boost Mode (BBM)**, by switching synchronously the MOSFETs Q_1 and Q_2 and the diodes D_1 and D_2. When 13.2V<V_{in}<15.4V the MOSFET Q_1 and the diode D_1 operate as a Buck converter, whereas the MOSFET Q_2 and the diode D_2 operate as a boost converter, with two different duty-cycles. Given the inductor L and the switching frequency f_s, the converter transits from **Continuous Conduction Mode (CCM)** to **Discontinuous Conduction Mode (DCM)** for different values of the input voltage V_{in} and the load current I_{out}, depending on the **BM/BBM** operation mode.

[(1)] Restricted range adopted for this educational board, compared to the 3V to 75V full range of LM5118 [5]

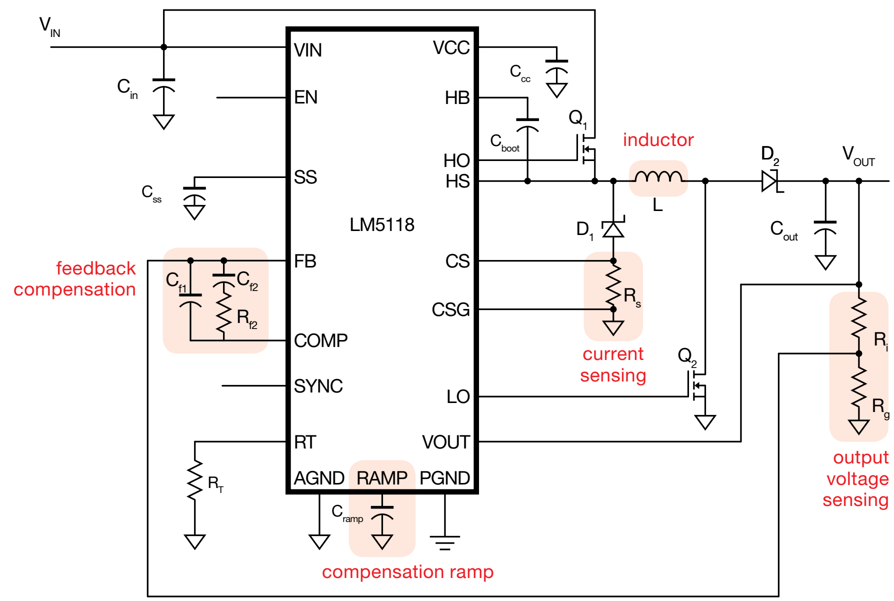


Figure 1. Simplified schematic of the LM5118 Buck-Boost regulator

Test#1. We investigate the operation of the Buck-Boost converter in CCM and in DCM. We measure the duty-cycle, while varying the input voltage and the load current. The DCM is detected by analyzing the inductor current waveform flowing through the current sensing resistor R_5 on the board. The duty-cycle is measured by analyzing the switching node voltage at TEST PIN TP_5. The test is performed for different input voltage and load current conditions, with different switching frequency set by jumper J_{15}. The mode of operation and the measured values of the duty-cycle are compared with the predictions of operation mode and of duty-cycle values assessed by means of theoretical formulae.

Test#2. We analyze the impact of the inductance on the CCM/DCM operation of the Buck boost converter, while varying th input voltage and the load current. The test is performed for three values of the load current and with two inductors available on the boards, selected by jumpers H_1-H_2-H_3. The goal is to see the effect of the inductance on the threshold value of input voltage bounding the transition from CCM to DCM, and to analyze the correlation with the theoretical formulae that predict the DCM operation.

Theory Background

The equations for steady-state analysis of the two-switches step-up-down converter in BM and BBM operation are summarized below. (*see [1]-[3] for more details on DCM operation and analysis and [5] for more details on LM5118 operation and features*)

Depending on the values of line voltage V_{in}, load current I_{out}, switching frequency f_s and inductance L, the LM5118 converter can enter four modes of operation: BM-CCM, BM-DCM, BBM-CCM, BBM-DCM. Figure 2 shows the plots of inductor current in such four operation modes.

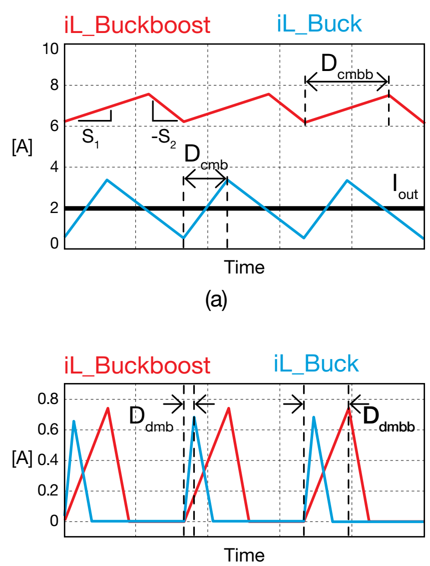


Figure 2. ——— V_{in}=36V, ——— V_{in}=6V; (a) CCM; (b) DCM

The expressions of duty-cycle, inductor current slopes, dc average, peak and valley values in CCM for the converter in Buck Mode and in Buck-Boost Mode are given in Table 1 (for an ideal loss-less converter):

Table 1

	Buck	Buck-Boost
D	M	M/(1+M)
s_1	$(V_{in}-V_{out})/L$	V_{in}/L
s_2	V_{out}/L	V_{out}/L
I_L	I_{out}	$I_{out}/(1-D)$
I_{pk}	$I_L+s_1D/(2f_s)$	
I_{vl}	$I_L-s_2D/(2f_s)$	

where $M=V_{out}/V_{in}$ [(1)]. Due to losses, the real duty-cycle D in CCM depends on the converter efficiency $\eta=P_{out}/P_{in}$:

(1) $D_{cmb}\approx M/\eta$; $D_{cmbb}\approx M/(\eta+M)$

Formulae (1) highlight that, when losses increase, the conversion ratio achieved with a given duty-cycle decreases, and the duty-cycle needed to get a given ratio conversion ratio M increases. The plots of Figures 3 and 4 show this property for the LM5118 Buck-Boost regulator with V_{out}=12V.

[(1)] the forward voltage drop of diodes can be added to V_{out} for more accurate analysis

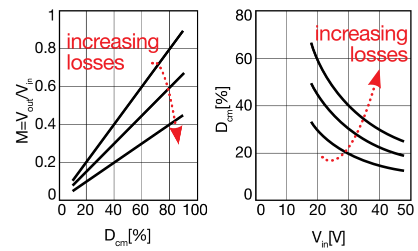


Figure 3. (a) conversion ratio vs duty-cycle and (b) duty-cycle vs input voltage in Buck Mode operation for increasing losses

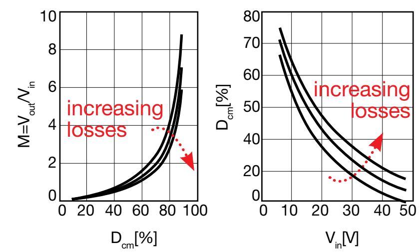


Figure 4. (a) conversion ratio vs duty-cycle and (b) duty-cycle vs input voltage in Buck-Boost Mode operation for increasing losses

Decreasing the load current or increasing the line voltage can lead the converter into DCM operation. The converter enters DCM when the average inductor current I_L is lower than one half of the peak to peak current ripple $\Delta i_{Lpp} = I_{pk}-I_{vl}$:

(2) $I_L < (I_{pk}-I_{vl})/2 \rightarrow$ DCM operation

According to (2), the converter in Buck Mode operates in DCM if one of the two following conditions is fulfilled:

(3) $I_{out}<I_{dcm,BM}=V_{out}(1-V_{out}/V_{in})/(2f_sL)$

(4) $V_{in}>V_{dcm,BM}=V_{out}/(1-2f_sLI_{out}/V_{out})$

The duty-cycle in BM DCM operation is:

(5) $D_{dmb}=M\sqrt{[K/(1-M)]}$

where $K=2f_sLI_{out}/V_{out}<1$ in DCM. According to (2), the converter in Buck-Boost Mode operates in DCM if one of the two following conditions is fulfilled:

(6) $I_{out}<I_{dcm,BBM}=V_{out}/[2f_sL(1+V_{out}/V_{in})^2]$

(7) $V_{in}>V_{dcm,BBM}=\sqrt{V_{out}}/[1/\sqrt{(2f_sLI_{out})}-1/\sqrt{V_{out}}]$

The duty-cycle in BBM DCM operation is:

(8) $D_{dmbb}=M\sqrt{K}$

Formulae (5) and (8) highlight that the duty-cycle value needed in DCM to achieve a given conversion ratio decreases when the load current decreases. Indeed, the duty-cycle directly impacts the energy transferred cycle-by-cycle to the load, through the inductor, in DCM operation. So that, a lower load current and a higher input voltage require a lower duty-cycle to achieve the desired output voltage $V_{out}=MV_{in}$.

Experiment set-up: configuration

The instruments needed for this experiment are: a DC POWER SUPPLY, one MULTIMETER, an OSCILLOSCOPE and a DC ELECTRONIC LOAD(*). Figure 5 shows the instruments connections. Follow the instructions provided in next page to set-up the connections.

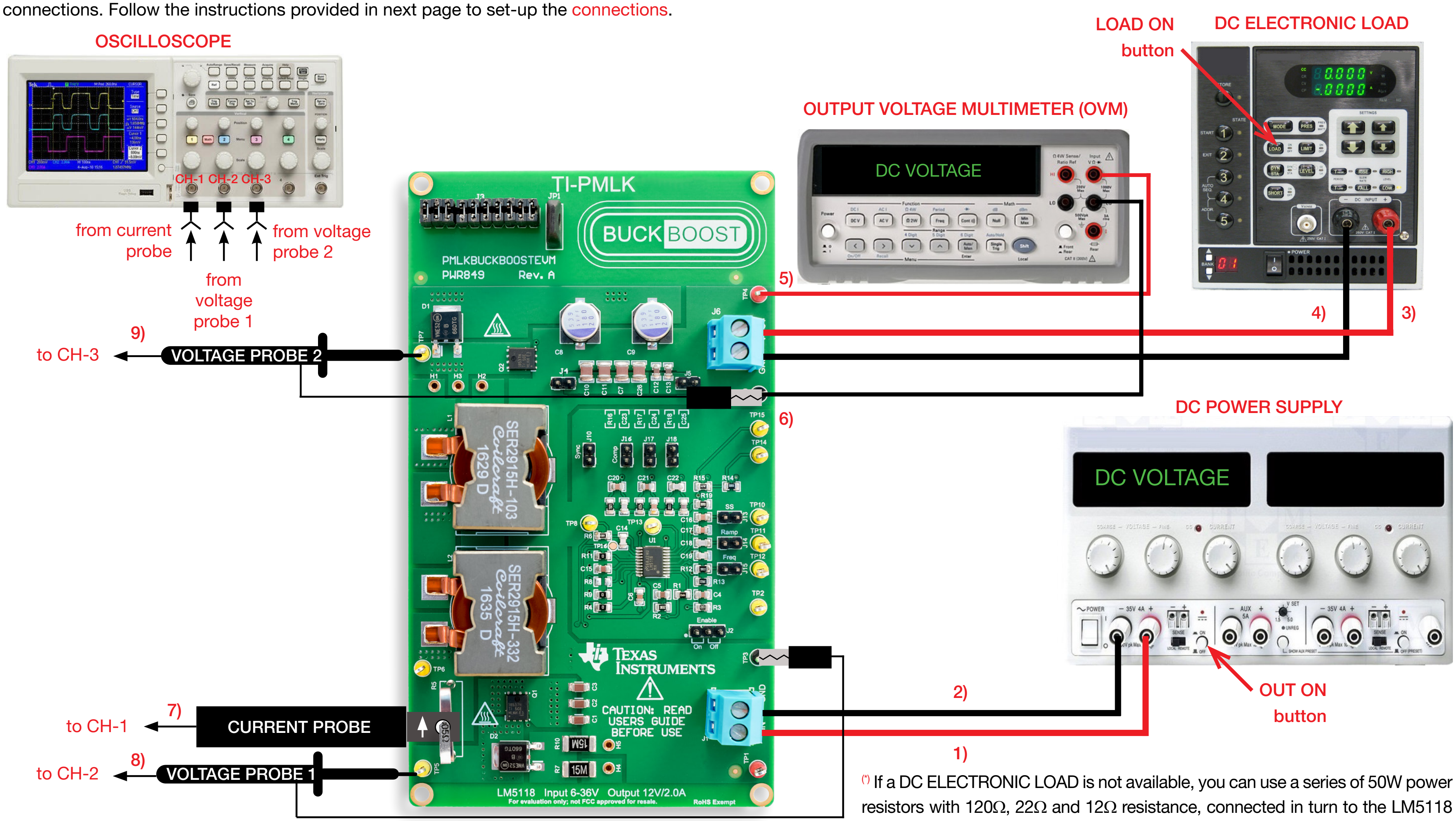


Figure 5. Experiment set-up.

(*) If a DC ELECTRONIC LOAD is not available, you can use a series of 50W power resistors with 120Ω, 22Ω and 12Ω resistance, connected in turn to the LM5118 regulator output, to obtain the load current values required in this Experiment.

Experiment set-up: instructions

With all the instruments turned off, make the following connections:

1) connect the POSITIVE (RED) OUTPUT of the DC POWER SUPPLY to the INPUT (VIN) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

2) connect the NEGATIVE (BLACK) OUTPUT of the DC POWER SUPPLY to the GROUND (GND) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

3) connect the OUTPUT (VOUT) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the POSITIVE (RED) INPUT of the ELECTRONIC LOAD

4) connect the GROUND (GND) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the NEGATIVE (BLACK) INPUT of the ELECTRONIC LOAD

5) connect the POSITIVE (RED) VOLTAGE INPUT of the OUPUT VOLTAGE MULTIMETER (OVM) to the TEST PIN TP_4 which is VOUT of the LM5118 Buck-Boost regulator

6) connect the NEGATIVE (BLACK) VOLTAGE INPUT of the OUTPUT VOLTAGE MULTIMETER (OVM) to the TEST PIN TP_9 which is GND of the LM5118 Buck-Boost regulator

7) connect a current probe to channel 1 of the oscilloscope and hang it on the sensing resistor R_5 of the LM5118 Buck-Boost regulator, ensuring that the arrow printed on the probe clamps corresponds to the current that enters the inductor (the arrow must point upside when looking the LM5118 Buck-Boost board frontally, as shown in Figure 5)

8) connect a voltage probe to channel 2 of the oscilloscope and hang it on the TEST PIN TP_5 which is the input side (Buck) switching node voltage of the LM5118 Buck-Boost regulator

9) connect a voltage probe to channel 3 of the oscilloscope and hang it on the TEST PIN TP_7 which is the output side (boost) switching node voltage of the LM5118 Buck-Boost regulator

[NOTES: for more accurate measurement of average input voltage, average input current and average output current, a four multimeters measurement setup can be adopted, as illustrated in *Experiment 1* of *TI-PMLK Boost Experiment Book [12]*]

Test#1: preparation and procedure

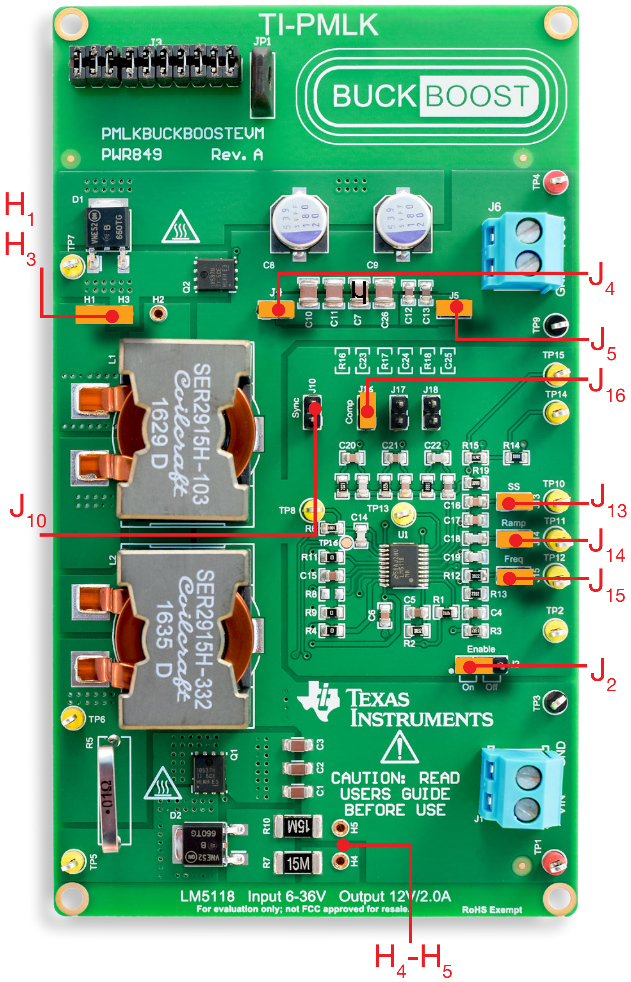


Figure 6. LM5118 board: jumpers set-up for Test#1

Initial jumpers set-up (see Figure 6):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **open** → switching frequency f_s = 150kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the MULTIMETER and set DC VOLTAGE MODE
2) turn on the OSCILLOSCOPE, set CH-1 in DC 50Ω coupling mode, set CH-2 and CH-3 in DC 1MΩ coupling mode, select CH-2 as trigger source, and execute the "de-gauss" of the current probe to remove dc bias
3) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
4) turn on the ELECTRONIC LOAD (with LOAD ON button OFF), set the CONSTANT CURRENT MODE, and set the current at 0.1A
5) turn ON the POWER SUPPLY "OUT ON" button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0A in the ELECTRONIC LOAD display, and a very small value in the DC POWER SUPPLY current display (if you do read values different than as described above, turn OFF the "OUT ON" button of the DC POWER SUPPLY and verify the previous steps)
6) turn ON the ELECTRONIC LOAD ON button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0.1A in the ELECTRONIC LOAD display, 0.12A in the DC POWER SUPPLY current display. On CH-1 of the OSCILLOSCOPE you should see a weveform with triangular impulses separated by intervals with oscillations, and waveforms with square impulses on CH-2 (zero to V_{in}) and CH-3 (zero to V_{out}), separated by intervals with oscillations (if the values you read and the waveforms you see do not look as described above, turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY and verify the experiment setup)
7) read the average input voltage value on the DC POWER SUPPLY voltage display, the average output voltage value on the MULTIMETER display, watch at the inductor current waveform on CH-1 of the OSCILLOSCOPE to assess whether the regulator is operating in CCM or DCM, measure the frequency and duty-cycle (watch the time when the voltage equals V_{in}) of the Buck switching node voltage on CH-2 of the OSCILLOSCOPE, and use these values according to *Measure and Calculate* section instructions. Repeat this step for all the load current and input voltage values listed in Table 1 (you do not need to turn OFF the POWER SUPPLY "OUT ON" button and the ELECTRONIC LOAD "LOAD ON" button while changing the input voltage and the load current)
8) turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY, short the jumper J_{15} to setup switching frequency f_s = 300kHz and repeat steps from 3) to 7)
9) at the end of the measurements, turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY, then switch off all the instruments.

Experiment 1

Test#1: measure and calculate

For each combination of the LM5118 Buck-Boost regulator switching frequency setup and operating conditions indicated in Table 1.

1) Predict the CCM/DCM operation based on the relation between I_{out} and I_{dcm} illustrated in the *Theory Background* section and fill the cell (1) with “CCM” or “DCM” label accordingly, verify whether the LM5118 boost regulator is operating in CCM or in DCM based on observation of the experimental inductor current waveform and fill the cell (2) with “CCM” or “DCM” label accordingly.
2) Based on the CCM/DCM operation predicted at point 1), calculate the duty-cycle D_{theo} by means of the formulae (1), (5) and (8) given in the *Theory Background* section and report the result in cell (3).
3) Measure the experimental duty-cycle D_{exp} of the LM5118 boost regulator and report the result in cell (4).

Table 1. Operation mode and duty-cycle of the Buck-Boost converter with **L = 10µH** and different operating conditions and switching frequency setup.

<table>
<tr><td>(1) theor. CCM/DCM</td><td>(2) exper. CCM/DCM</td><td colspan="6">f_s = 150kHz</td><td colspan="6">f_s = 300kHz</td></tr>
<tr><td>(3) theor. D_{theo} [%]</td><td>(4) exper. D_{exp} [%]</td><td colspan="2">I_{out}=0.1A</td><td colspan="2">I_{out}=0.5A</td><td colspan="2">I_{out}=1.0A</td><td colspan="2">I_{out}=0.1A</td><td colspan="2">I_{out}=0.5A</td><td colspan="2">I_{out}=1.0A</td></tr>
<tr><td colspan="2" rowspan="2">V_{in}=10V (Buck-Boost Mode)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td></tr>
<tr><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td></tr>
<tr><td colspan="2" rowspan="2">V_{in}=20V (Buck Mode)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td><td>(1)</td><td>(2)</td></tr>
<tr><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td><td>(3)</td><td>(4)</td></tr>
</table>

Inductor:
H_1-H_3 **shorted** → inductor L_1 (ferrite core, 10µH, 23.4A, 1.86mΩ) connected
H_2-H_3 **shorted** → inductor L_2 (ferrite core, 3.3µH, 30A, 1.86mΩ) connected

Switching frequency:
J_{15} **open** → f_s = 150kHz
J_{15} **shorted** → f_s = 300kHz

Operation mode:
V_{in} **< 13.2V** → Buck-Boost Mode (BBM)
V_{in} **> 15.4V** → Buck Mode (BM)

Answer:

1. Is the duty-cycle in DCM operation lower than in CCM operation? ☐ yes ☐ no ☐ it depends on load current ☐ it depends on line voltage
2. Does the experimental duty-cycle increase with the load current? ☐ yes ☐ no ☐ it does in DCM operation ☐ it does in CCM operation
3. Does a higher switching frequency facilitate DCM operation? ☐ yes ☐ no ☐ it depends on line voltage ☐ it depends on load current

Test#2: preparation and procedure

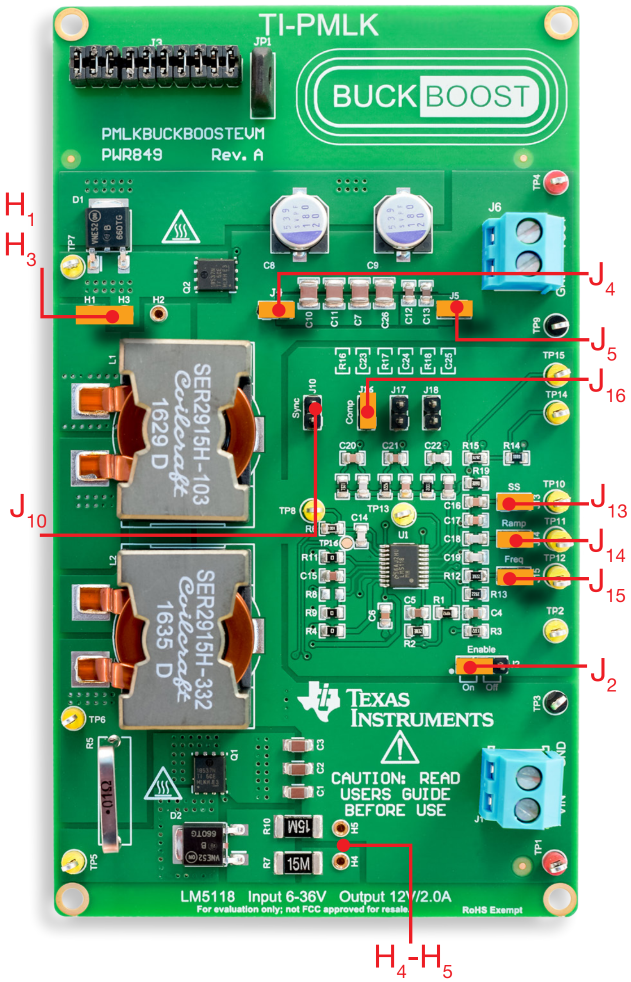


Figure 7. LM5118 board: jumpers set-up for Test#2

Initial jumpers set-up (see Figure 7):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** →C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with
  $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the MULTIMETER and set DC VOLTAGE MODE
2) turn on the OSCILLOSCOPE, set CH-1 in DC 50Ω coupling mode, set CH-2 and CH-3 in DC 1MΩ coupling mode, select CH-2 as trigger source, and execute the “de-gauss” of the current probe to remove dc bias
3) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 22V, and set the CURRENT LIMIT > 7A
4) turn on the ELECTRONIC LOAD (with LOAD ON button OFF), set the CONSTANT CURRENT MODE, and set the current at 0.1A
5) turn ON the POWER SUPPLY “OUT ON” button and adjust the DC POWER SUPPLY knob until you read 22V in the display. In these conditions you should read about 12V in the MULTIMETER display, 0A in the ELECTRONIC LOAD current display, and a very small value in the DC POWER SUPPLY current display (if you do read values different than as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
6) turn ON the ELECTRONIC LOAD ON button and adjust the DC POWER SUPPLY knob until you read 22V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0.1A in the ELECTRONIC LOAD current display, about 0.055A in the DC POWER SUPPLY current display. On CH-1 of the OSCILLOSCOPE you should and see a weveform with triangular impulses separated by intervals with oscillations, and waveforms with square impulses on CH-2 (zero to V_{in}) and CH-3 (zero to V_{out}), separated by intervals with oscillations (if the values you read and the waveforms you see do not look as described above, turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY and verify the experiment setup)
7) while slowly decreasing the input voltage from 22V to 16V, read the average input voltage on the DC POWER SUPPLY voltage display, watch the inductor current waveform on CH-1 of the OSCILLOSCOPE to assess whether the regulator is operating in CCM or DCM, detect the minimum input voltage value for which the regulator operates in DCM, and report the value in Table 2. Repeat this step for all the load current values listed in Table 2 (you do not need to turn OFF the POWER SUPPLY “OUT ON” button and the ELECTRONIC LOAD “LOAD ON” button while changing the input voltage and the load current)
8) repeat step 7) with input voltage starting at 12V and decreasing down to 6V
9) turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, remove the jumper shorting H_1-H_3, short H_2-H_3 to setup the inductance L = 3.3µH and repeat steps from 3) to 8)
10) at the end of the measurements, turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, then switch off all the instruments.

Experiment 1

Test#2: measure and calculate

For each combination of inductance L and load current I_{out} indicated in Table 2:

1) For input voltage decreasing from 22V to 16V, which determines BBM operation, report into the cell (1) the minimum input voltage $\mathbf{V_{dcm,BM}}$ for which the LM5118 boost regulator operates in DCM, based on the observation of the experimental inductor current waveform, and report into the cell (2) the theoretical value predicted by the formula (4) provided in the *Theory Background* section.
2) For input voltage decreasing from 12V to 6V, which determines BBM operation, report into the cell (3) the minimum input voltage $\mathbf{V_{dcm,BBM}}$ for which the LM5118 boost regulator operates in DCM, based on the observation of the experimental inductor current waveform, and report into the cell (2) the theoretical value predicted by the formula (7) provided in the *Theory Background* section.

Table 2. Impact of load current and inductance on the input voltage DCM operation range of LM5118 Buck-Boost converter with f_s = 300kHz

(1) $V_{dcm,BM,ex}$ [V] / (2) $V_{dcm,BM,th}$ [V] / (3) $V_{dcm,BBM,ex}$ [V] / (4) $V_{dcm,BBM,th}$ [V]	L = L_1 = 10µH						L = L_2 = 3.3µH					
I_{out}=0.1A	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)
I_{out}=0.5A	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)
I_{out}=1.0A	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)

Inductor:
H_1-H_3 **shorted** → inductor L_1 (ferrite core, 10µH, 23.4A, 1.86mΩ) connected
H_2-H_3 **shorted** → inductor L_2 (ferrite core, 3.3µH, 30A, 1.86mΩ) connected

Switching frequency:
J_{15} **open** → f_s = 150kHz
J_{15} **shorted** → f_s = 300kHz

Operation mode:
V_{in} **< 13.2V** → Buck-Boost Mode (BBM)
V_{in} **> 15.4V** → Buck Mode (BM)

Answer:

1. Does a higher load current expand the input voltage range where the Buck boost regulator operates in DCM?

☐ yes ☐ no, it reduces the range ☐ it depends on the inductance ☐ comments: ____________________

2. Identify the main factors determining the reduction of input voltage range where the converter operates in DCM, for BM and for BBM: ____________________

3. Are the experimental vaues of $\mathbf{V_{dcm,BBM}}$ and $\mathbf{V_{dcm,BM}}$ consistent with the theoretical values?

☐ yes ☐ no ☐ it depends on inductance ☐ it depends on load current ☐ comments: ____________________

Discussion

In Test#1 we are interested in detecting the CCM/DCM operation mode and measuring the duty-cycle of a Buck-Boost regulator, at different input voltage, load current and frequency.

As illustrated in the introductory *Case Study* section, the LM5118 Buck-Boost regulator has two different modes of operation, Buck Mode and Buck-Boost Mode. The 20V and 10V input voltage setups used in Test#1 allow us to observe the LM5118 in the Buck Mode as well as in the Buck-Boost Mode. The DCM operation can be detected in both the Buck Mode and Buck-Boost Mode, by observing the waveforms of the inductor current i_L and of the input side switching node voltage (*see Figure 1*). The DCM operation can be assessed by detecting whether there is a zero crossing in the inductor current waveform, while the duty-cycle can be determined by the measuring the duration t_{Q1} of the time interval wherein the input side switching node voltage is clamped to the input voltage V_{in} due to the MOSFET Q_1 conduction (*see Figures 8 and 9 on next page*). The theoretical waveforms of inductor currrent in CCM and DCM are shown in the Figure 2 of the *Theory Background* section. When a DC-DC converter operates in DCM, the inductor current drops to zero before the end of the switching period, and stays at zero until the next switching cycle starts. In theory, during this dead interval the inductor voltage should be zero. When the LM5118 Buck-Boost regulator operates in Buck Mode, the MOSFET Q_2 is permanently OFF and the output side switching node is then connected to the output voltage node through the diode D_2. When the LM5118 regulator in Buck Mode operates in DCM, during the dead interval the MOSFET Q_1 and the diode D_1 are both OFF. In these conditions, the input side switching node voltage drops below the input voltage and keeps, in theory, at a constant value depending on the impedances of the MOSFET Q_1 and the diode D_1 in the OFF state. In reality, during the dead interval the parasitic capacitances of the MOSFETs Q_1 and Q_2 and of the diodes D_1 and D_2 form a resonant loop with the inductor, which causes oscillations in the inductor current, in the input side switching node voltage and in the output side switching node voltage, as shown in Figure 9. When the LM5118 Buck-Boost regulator operates in Buck-Boost Mode, the MOSFET Q_2 and the diode D_2 are switching too. At 10V input voltage, the duty-cycle of the two switching couples Q_1-D_1 an Q_2-D_2 is the same. When the LM5118 regulator in Buck-Boost Mode operates in DCM, during the dead interval we also see oscillations in the inductor current and in the switching node voltages, as shown in Figure 11.
The formulae (3)(4)(6)(7) provided in the *Theory Background* section show that the LM5118 Buck-Boost regulator enters DCM when the load current I_{out} is lower than a critical threshold I_{crit}, or when the input voltage is higher than a critical thresholds V_{dcm}. The current and voltage thresholds I_{dcm} and V_{dcm} bounding the transition from CCM to DCM operation change depending on whether the regulator is operating in Buck Mode or in Buck-Boost Mode. Formulae (3) and (4) are valid for Buck Mode, whereas formulae (6) and (7) are valid for Buck-Boost Mode. The formulae (3)(4)(6)(7) show that a higher switching frequency f_s helps expand the range of operation in CCM, for both Buck Mode and Buck-Boost Mode. Indeed, a higher switching frequency reduces the duration of interval of time where the inductor discharges while its current rolls off, thus preventing the zero current crossing. The expected result of experimental measurements is that, when the switching frequency is increased, for a given setting of input voltage and load current, either the operation mode can switch from DCM to CCM or the duration of the dead interval of DCM operation can be reduced.

[**NOTE:** the formulae (3)(4)(6)(7) are valid for $f_s<V_{out}/(2I_{out}L)$]

In Test#2 we are interested in analyzing the impact of the inductor on the threshold value of input voltage for DCM operation of the Buck-Boost regulator, at different load currents.

The formulae (3)(4)(7)(8) provided in the *Theory Background* section show that a higher inductance selection helps expand the range of operation in CCM, for both Buck Mode and Buck-Boost Mode. Indeed, a higher inductance reduces the slope of the inductor current during the inductor discharge, thus, requiring a longer time for the zero current crossing occurs. The expected result of the experiment is that, for a given value of the load current, when the inductance value is decreased, the threshold value of the input voltage V_{in} which determines the transition from CCM to DCM decreases.

Experimental plots

The plots collected in the Figures 8 to 11 show the inductor current and the switching nodes voltage of the LM5118 Buck-Boost regulator in different operating conditions.

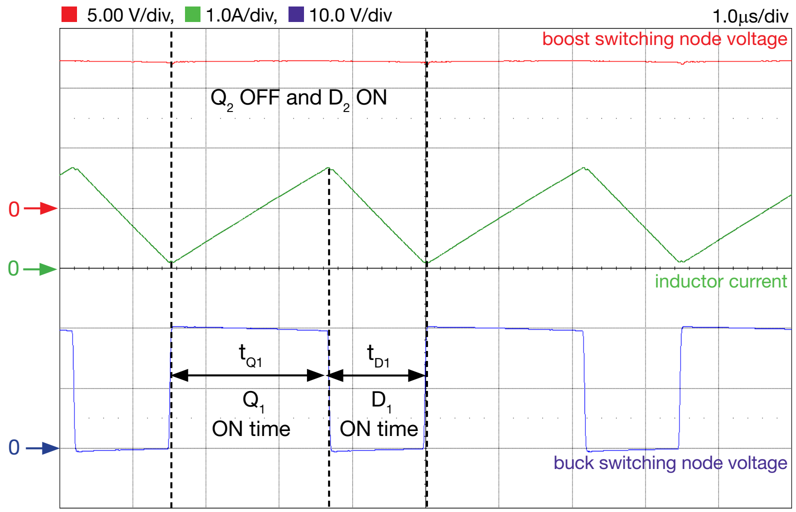


Figure 8. LM5118 regulator in steady-state CCM Buck-Boost operation: V_{in}=20V, I_{out}=1.0A, f_s=300kHz, L=10µH

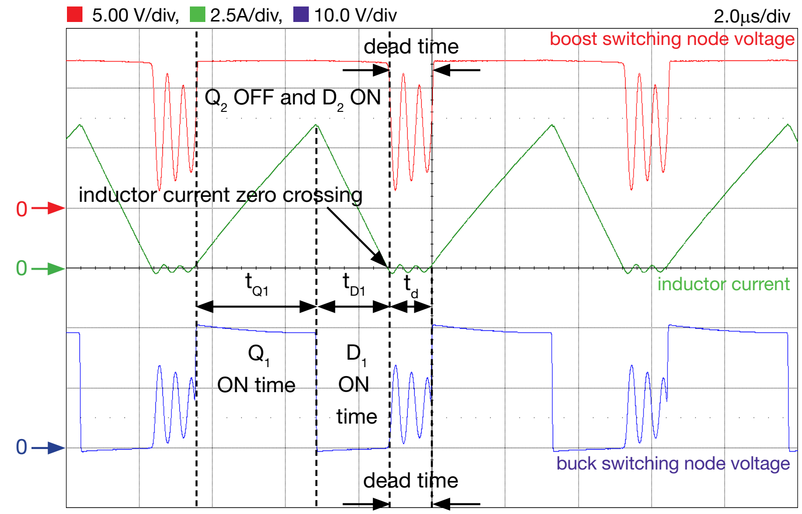


Figure 9. LM5118 regulator in steady-state DCM Buck operation: V_{in}=20V, I_{out}=1.0A, f_s=150kHz, L=10µH

Figures 8 and 9 highlight the difference between the waveforms of the LM5118 regulator in steady-state CCM Buck Mode operation (Figure 8) and in steady-state DCM Buck Mode operation (Figure 9). The difference in CCM/DCM operation mode is determined by the decrease of the switching frequency from 300kHz to 150kHz. You can observe that the duty-cycle in CCM, given by $D_{cmb}=t_{Q1}/(t_{Q1}+t_{D1})$, is higher than the duty-cycle in DCM, given by $D_{dmb}=t_{Q1}/(t_{Q1}+t_{D1}+t_d)$ (compare the measured values of duty-cycle with the results obtained by the application of the formulae (1) for CCM and (5) for DCM provided in the *Theory Background* section). You can also observe that the voltage of the output side switching node (boost) is flat in CCM operation (Figure 8). In DCM, you can see oscillations during the dead time interval on both the input and the output side switching node voltages (Figure 9). This is due to the resonance loop formed by the inductor and the parasitic capacitances associated with the MOSFETs and diodes. Indeed, also the diode D_2 turns OFF during the dead interval, after the inductor current zero crossing instant highlighted in Figure 9.

Experimental plots

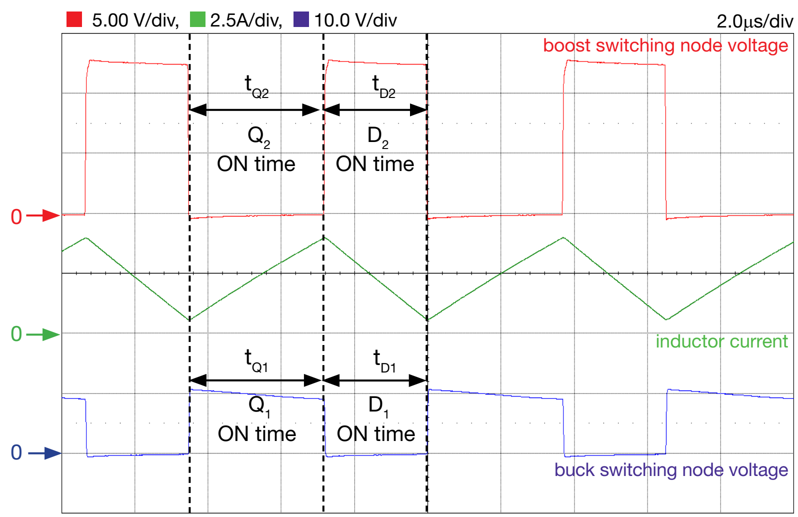


Figure 10. LM5118 regulator in steady-state CCM Buck-Boost operation: V_{in}=10V, I_{out}=1.0A, f_s=150kHz, L=10µH

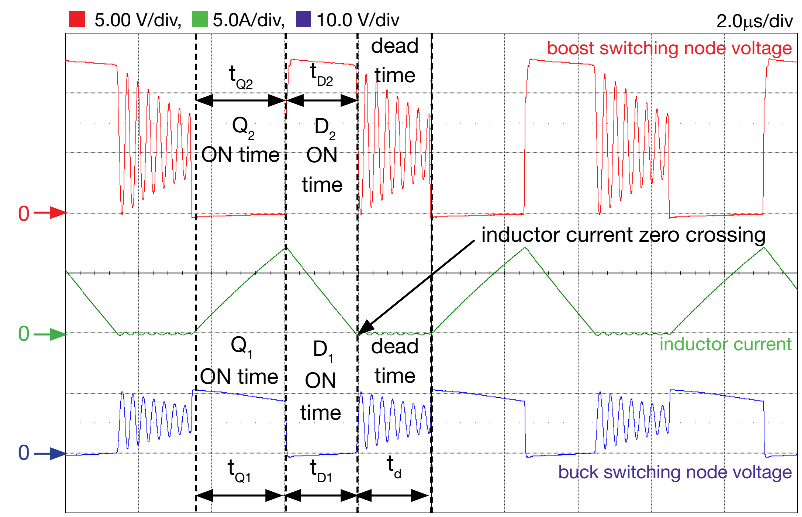


Figure 11. LM5118 regulator in steady-state DCM Buck-Boost operation: V_{in}=10V, I_{out}=1.0A, f_s=150kHz, L=3.3µH

Figures 10 and 11 highlight the difference between the waveforms of the LM5118 regulator in steady-state CCM Buck-Boost Mode operation (Figure 10) and in steady-state DCM Buck-Boost Mode operation (Figure 11). The difference in CCM/DCM operation mode is determined by the decrease of the inductance from 10µH to 3.3µH. You can observe that the duty-cycle in CCM, given by $D_{cmbb}=t_{Q1}/(t_{Q1}+t_{D1})$, is higher than the duty-cycle in DCM, given by $D_{dmbb}=t_{Q1}/(t_{Q1}+t_{D1}+t_d)$ (compare the measured values of duty-cycle with the results obtained by the application of the formulae (1) for CCM and (8) for DCM provided in the *Theory Background* section). You can also observe that the voltage of the output side switching node (boost) swings between ground and output voltage in CCM operation (Figure 10). In DCM, you can see oscillations during the dead time interval on both the input and the output side switching node voltages (Figure 11). This is due to the resonance loop formed by the inductor and the parasitic capacitances associated with the MOSFETs and diodes.

Experiment 2

The goal of this experiment is to analyze the impact of the operating conditions and of the operation mode on the power losses and efficiency of the Buck-Boost converter.

Case Study

The goal of this experiment is to analyze how the input voltage and load current and the operation mode influence the power losses and the efficiency of the Buck-Boost converter.

The TI-PMLK LM5118 Buck-Boost regulator operates with V_{in}=[6,36]V[(1)], while regulating the output voltage at the nominal value V_{out}=12V in the load current range I_{out}=[0,2]A. Fig.1 shows the simplified circuit schematic of the regulator. The LM5118 Buck-Boost regulator is based on the two-switches two-diodes topology, which allows to achieve non inverting step-up-down voltage conversion. The LM5118 controller senses the input voltage and drives the switches so that the converter operates in **Buck Mode (BM)** when V_{in}>15.4V, by switching the MOSFET Q_1 and the diode D_1, while the MOSFET Q_2 and the diode D_2 are permanently OFF and ON, respectively. When V_{in}<13.2V the converter operates in **Buck-Boost Mode (BBM)**, by switching synchronously the MOSFETs Q_1 and Q_2 and the diodes D_1 and D_2. When 13.2V<V_{in}<15.4V the MOSFET Q_1 and the diode D_1 operate as a Buck converter, whereas the MOSFET Q_2 and the diode D_2 operate as a boost converter, with two different duty-cycles. The efficiency of the converter is influenced by the total losses of power passive components and of semiconductor devices, which in turn are conditioned by the particular combination of BM or BBM operation and Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM) operation.

[(1)] Restricted range adopted for this educational board, compared to the 3V to 75V full range of LM5118 [5]

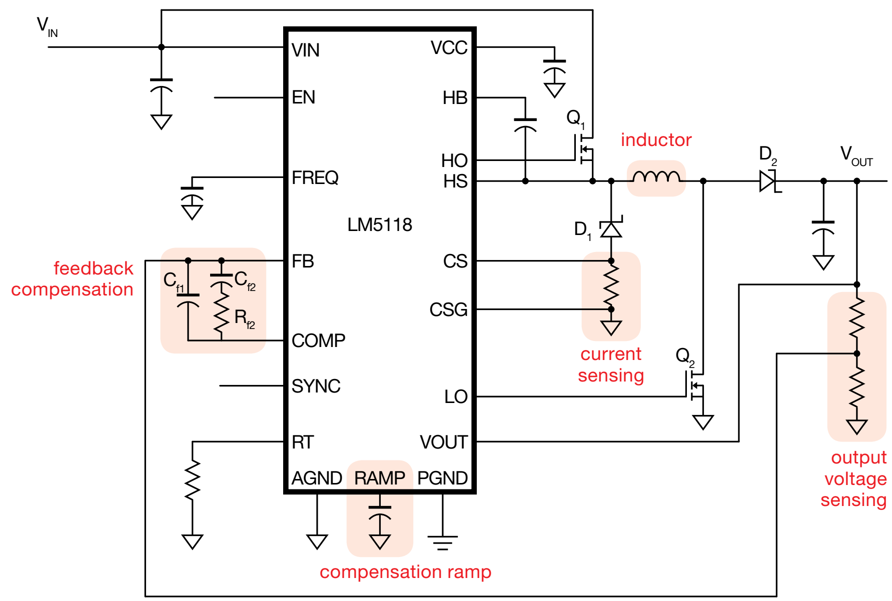


Figure 1. Simplified schematic of the LM5118 Buck-Boost regulator

Test#1. We investigate the operation of the Buck-Boost converter in CCM and in DCM, and we measure the power losses while varying the input voltage and the load current. The DCM is detected by analyzing the inductor current waveform flowing through the current sensing resistor R_5 on the board. The experimental power losses are obtained as difference between the measured input power and output power. The test is performed for given input voltage and load current conditions and with different setup of jumper J_{15}, which sets the switching frequency. The measured power losses are compared with the power losses of MOSFETs, diodes, inductor and current sensing resistor predicted by theoretical formulae.

Test#2. We analyze the impact of the inductance on the power losses of the Buck-Boost converter, while varying the input voltage and the load current. The test is performed under five values of the load current, two values of the input voltage, and two values of inductance selected by jumpers H_1-H_2-H_3. The goal is to analyze the effect of the inductor on the power losses and correlate the experimental measurement of the power losses with the values calculated using the theoretical formulae provided.

Theory Background

The losses of MOSFETs and diodes in the LM5118 Buck-Boost converter can be analyzed by means of the following simplified formulae (*see [1]-[3] for more details on Buck-Boost topology operation and CCM/DCM modeling, [2] for MOSFETs losses calculation, [5] for details on LM5118 operation and features, Figure 1 to determine inductor, MOSFETs and diodes voltages and currents*)

Figure 2 shows the inductor current waveforms of the LM5118 Buck-Boost regulator in Buck Mode (BM) and in Buck-Boost Mode (BBM), for CCM and DCM operation.

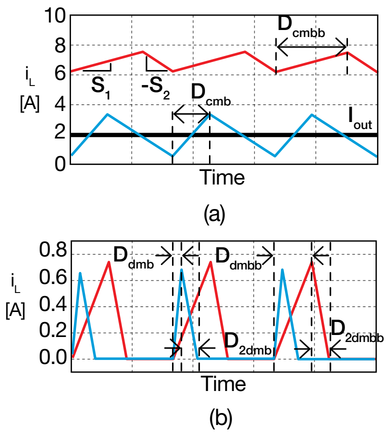


Figure 2. —— V_{in}=36V; —— V_{in}=6V; (a) CCM; (b) DCM

The LM5118 converter in Buck Mode operates in DCM if one of the two following conditions is fulfilled:

(1) $I_{out} < I_{dcm,BM} = V_{out}(1-V_{out}/V_{in})/(2f_sL)$

(2) $V_{in} > V_{dcm,BM} = V_{out}/(1-2f_sLI_{out}/V_{out})$

The converter in Buck-Boost Mode operates in DCM if one of the two following conditions is fulfilled:

(3) $I_{out} < I_{dcm,BBM} = V_{out}/[2f_sL(1+V_{out}/V_{in})^2]$

(4) $V_{in} > V_{dcm,BBM} = \sqrt{V_{out}}/[1/\sqrt{(2f_sLI_{out})}-1/\sqrt{V_{out}}]$

Type of losses	BM-CCM losses	BM-DCM losses	BBM-CCM losses	BBM-DCM losses
MOSFET conduction:	$R_{ds} D_{cmb} I_{Lb}^2 \alpha_b$	$\frac{1}{3} R_{ds} I_{pkb}^2 D_{dmb}$	$2R_{ds} D_{cmbb} I_{Lbb}^2 \alpha_{bb}$	$\frac{2}{3} R_{ds} I_{pkbb}^2 D_{dmbb}$
MOSFET switching:	$\frac{1}{2} V_{in} f_s (I_{vlb} t_{on} + I_{pkb} t_{off})$	$\frac{1}{2} V_{in} f_s I_{pkb} t_{off}$	$\frac{1}{2} V_{tot} f_s (I_{vlbb} t_{on} + I_{pkbb} t_{off})$	$\frac{1}{2} V_{tot} f_s I_{pkbb} t_{off}$
MOSFET gate:	$Q_g V_{dr} f_s$	$Q_g V_{dr} f_s$	$2Q_g V_{dr} f_s$	$2Q_g V_{dr} f_s$
diode conduction:	$(V_{fD2} + V_{fD1} D'_{cmb}) I_{Lb} \alpha_b$	$(I_{Lb} V_{fD2} + \frac{1}{2} D_{2dmb} I_{pkb} V_{fD1})$	$(V_{fD1} + V_{fD2}) D'_{cmbb} I_{Lbb} \alpha_b$	$\frac{1}{2}(V_{fD1} + V_{fD2}) D_{2dmbb} I_{pkbb}$
sensing resistor: (in series with D_1)	$R_s D'_{cmb} I_{Lb}^2 \alpha_b$	$\frac{1}{3} R_s I_{pkb}^2 D_{2dmb}$	$R_s D'_{cmbb} I_{Lbb}^2 \alpha_{bb}$	$\frac{1}{3} R_s I_{pkbb}^2 D_{2dmbb}$
inductor conduction:	$R_L I_{Lb}^2 \alpha_b$	$\frac{1}{3} R_L I_{pkb}^2 (D_{dmb} + D_{2dmb})$	$R_L I_{Lbb}^2 \alpha_{bb}$	$\frac{1}{3} R_L I_{pkb}^2 (D_{dmb} + D_{2dmb})$
	$D_{cmb} \cong M$	$D_{dmb} \cong \frac{M}{\sqrt{1-M}} \sqrt{K}$	$D_{cmbb} \cong \frac{M}{1+M}$	$D_{dmbb} \cong M\sqrt{K}$
	$\alpha_b = 1 + \Delta i_b^2 / (12 I_{Lb}^2)$	$D_{2dmb} = I_{pkb} f_s L / V_{out}$	$\alpha_{bb} = 1 + \Delta i_{bb}^2 / (12 I_{Lbb}^2)$	$D_{2dmbb} = I_{pkbb} f_s L / V_{out}$
	$I_{Lb} = I_{out}$	$I_{Lb} = \frac{1}{2} I_{pkb} (D_{dmb} + D_{2dmb})$	$I_{Lbb} = I_{out} / D'_{cmbb}$	$I_{Lbb} = \frac{1}{2} I_{pkbb} (D_{dmbb} + D_{2dmbb})$
	$I_{pkb}, I_{vlb} = I_{Lb} \pm \frac{1}{2} \Delta i_b$	$I_{pkb} = (V_{in} - V_{out}) D_{dmb} / (f_s L)$	$I_{pkbb}, I_{vlbb} = I_{Lbb} \pm \frac{1}{2} \Delta i_{bb}$	$\Delta i_{bb} = V_{in} D_{dmbb} / (f_s L)$
	$\Delta i_b = (V_{in} - V_{out}) D_{cmb} / (f_s L)$	$K = 2f_sLI_{out}/V_{out}$	$\Delta i_{bb} = V_{in} D_{cmbb} / (f_s L)$	$K = 2f_sLI_{out}/V_{out}$

$$M = \frac{V_{out}}{V_{in}} \; ; \; V_{tot} = V_{in} + V_{out} \; ; \; t_{on} = \frac{Q_{gsw} R_{gate}}{V_{dr} - V_{th} - I_{vlx} / g_{fs}} \; ; \; t_{off} = \frac{Q_{gsw} R_{gate}}{V_{th} + I_{pkx} / g_{fs}} \; ; \; D'_{cmx} = 1 - D_{cmx}; \; x = b, bb$$

Good to know:

1. the MOSFETs loss formulae are valid if the devices Q_1 and Q_2 are identical;
2. the gate resistance R_{gate} is the sum of the MOSFET internal gate resistance R_{gint} and of the gate driver resistance R_{dr}: $R_{gate}=R_{gint}+R_{dr}$;
3. the magnetic core of the inductor is affected by power losses (see *Experiment 2* in *TI-PMLK Boost Experiment Book*)
4. A more accurate value of the duty-cycle D can be obtained as the ratio of the theoretical value and the efficiency η of the converter (η=90%-95%)

Experiment set-up: configuration

The instruments needed for this experiment are: a DC POWER SUPPLY, one MULTIMETER, an OSCILLOSCOPE and a DC ELECTRONIC LOAD(*). Figure 3 shows the instruments connections. Follow the instructions provided in next page to set-up the connections.

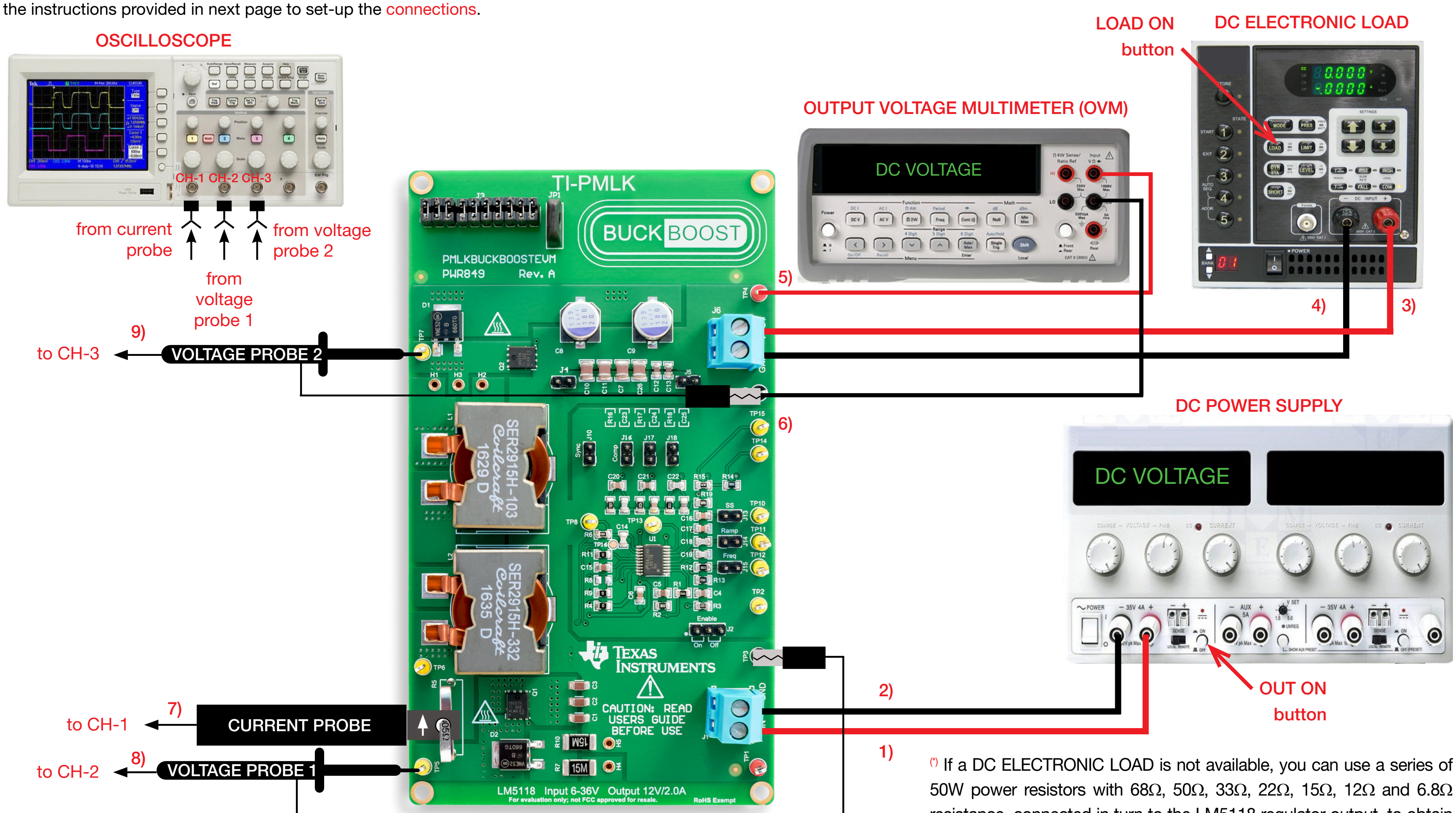


Figure 3. Experiment set-up.

(*) If a DC ELECTRONIC LOAD is not available, you can use a series of 50W power resistors with 68Ω, 50Ω, 33Ω, 22Ω, 15Ω, 12Ω and 6.8Ω resistance, connected in turn to the LM5118 regulator output, to obtain the load current values required in this Experiment.

Experiment set-up: instructions

With all the instruments turned off, make the following connections:

1) connect the POSITIVE (RED) OUTPUT of the DC POWER SUPPLY to the INPUT (VIN) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

2) connect the NEGATIVE (BLACK) OUTPUT of the DC POWER SUPPLY to the GROUND (GND) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

3) connect the OUTPUT (VOUT) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the POSITIVE (RED) INPUT of the ELECTRONIC LOAD

4) connect the GROUND (GND) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the NEGATIVE (BLACK) INPUT of the ELECTRONIC LOAD

5) connect the POSITIVE (RED) VOLTAGE INPUT of the OUPUT VOLTAGE MULTIMETER (OVM) to the TEST PIN TP_4 which is VOUT of the LM5118 Buck-Boost regulator

6) connect the NEGATIVE (BLACK) VOLTAGE INPUT of the OUTPUT VOLTAGE MULTIMETER (OVM) to the TEST PIN TP_9 which is GND of the LM5118 Buck-Boost regulator

7) connect a current probe to channel 1 of the oscilloscope and hang it on the sensing resistor R_5 of the LM5118 Buck-Boost regulator, ensuring that the arrow printed on the probe clamps corresponds to the current that enters the inductor (the arrow must point upside when looking the LM5118 Buck-Boost board frontally, as shown in Figure 5)

8) connect a voltage probe to channel 2 of the oscilloscope and hang it on the TEST PIN TP_5 which is the input side (Buck) switching node voltage of the LM5118 Buck-Boost regulator

9) connect a voltage probe to channel 3 of the oscilloscope and hang it on the TEST PIN TP_7 which is the output side (boost) switching node voltage of the LM5118 Buck-Boost regulator

[NOTE: for more accurate measurement of average input voltage, average input current and average output current, a four multimeters measurement setup can be adopted, as illustrated in *Experiment 2* of *TI-PMLK Boost Experiment Book [12]*]

Test#1: preparation and procedure

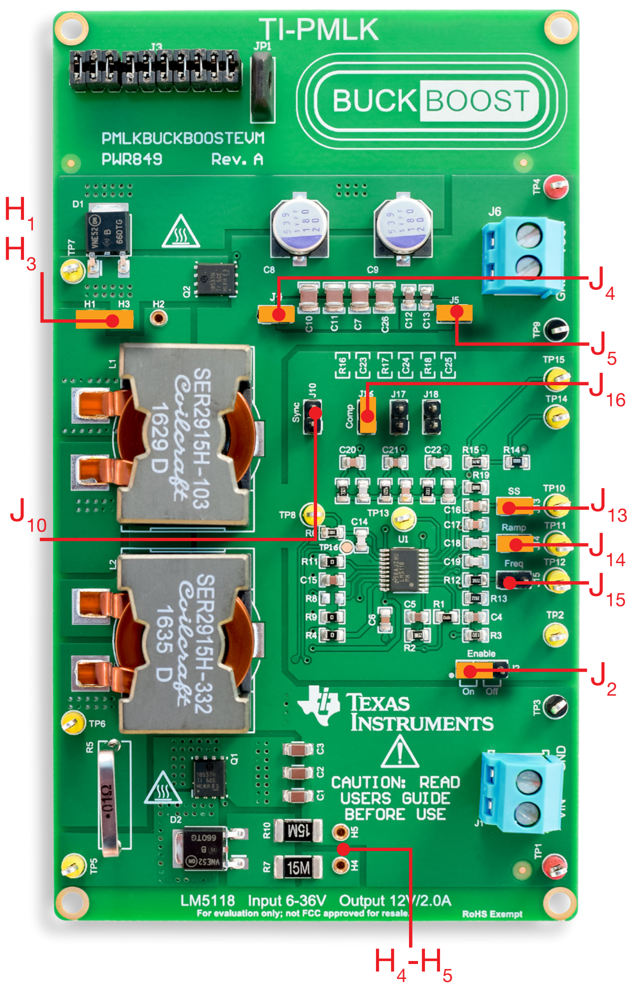


Figure 4. LM5118 board: jumpers set-up for Test#1

Initial jumpers set-up (see Figure 4):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **open** → switching frequency f_s = 150kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the MULTIMETER and set DC VOLTAGE MODE
2) turn on the OSCILLOSCOPE, set CH-1 in DC 50Ω coupling mode, set CH-2 and CH-3 in DC 1MΩ coupling mode, select CH-2 as trigger source, and execute the "de-gauss" of the current probe to remove dc bias
3) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
4) turn on the ELECTRONIC LOAD (with LOAD ON button OFF), set the CONSTANT CURRENT MODE, and set the current at 0.25A
5) turn ON the POWER SUPPLY "OUT ON" button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0A in the ELECTRONIC LOAD display, and a very small value in the DC POWER SUPPLY current display (if you do read values different than as described above, turn OFF the "OUT ON" button of the DC POWER SUPPLY and verify the previous steps)
6) turn ON the ELECTRONIC LOAD ON button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0.25A in the ELECTRONIC LOAD display, 0.30A in the DC POWER SUPPLY current display. On CH-1 of the OSCILLOSCOPE you should and see a weveform with triangular impulses separated by intervals with oscillations, and waveforms with square impulses on CH-2 (zero to V_{in}) and CH-3 (zero to V_{out}), separated by intervals with oscillations (if the values you read and the waveforms you see do not look as described above, turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY and verify the experiment setup)
7) read the average input voltage value on the DC POWER SUPPLY voltage display, the average output voltage value on the MULTIMETER display, the average input current in the DC POWER SUPPLY current display and the average output current in the ELECTRONIC LOAD display
8) watch the inductor current waveform on CH-1 of the OSCILLOSCOPE to assess whether the regulator is operating in CCM or DCM, measure the peak, the valley and the average value of the inductor current, measure the frequency and duty-cycle of the Buck switching node voltage (watch the time when the voltage equals V_{in}) on CH-2 of the OSCILLOSCOPE, and use these values according to *Measure and Calculate* section instructions. Repeat this step for all load current and input voltage values listed in Table 1
9) turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY, short the jumper J_{15} to setup switching frequency f_s = 300kHz and repeat steps from 3) to 8)
10) at the end of the measurements, turn OFF the ELECTRONIC LOAD "LOAD ON" button and the DC POWER SUPPLY "OUT ON" button, then switch off all the instruments.

Test#1: measure and calculate

For the operating conditions indicated in Table 1:

1) Measure the average input voltage V_{in}, input current I_{in}, output voltage V_{out} and output current I_{out}, the switching frequency f_s, the duty-cycle D, the peak and valley values I_{pk} and I_{vl} of the inductor current.
2) Assess whether the regulator operates in CCM or DCM by observing the inductor current (in CCM operation the valley current I_{vl} at the beginning of the switching cycle is positive) (*see also Experiment 1*).
3) Based on the CCM/DCM assessment, and on the BM/BBM operation, use the appropriate formulae provided in the *Theory Background* section to calculate the sum of power losses of MOSFETs, diodes, inductor and sensing resistance, then calculate the experimental power losses $P_{dexp} = V_{in} I_{in} - V_{out} I_{out}$ and report the results in Table 1.

Table 1. Power losses of the Buck-Boost converter operating with **$L = 10\mu H$** and different operating conditions and switching frequency setup.

(1) theor. CCM/DCM	(2) exper. CCM/DCM	f_s = 150kHz						f_s = 300kHz					
(3) theor. loss [mW]	(4) exper. loss [mW]	I_{out}=0.25A		I_{out}=1.00A		I_{out}=1.75A		I_{out}=0.25A		I_{out}=1.00A		I_{out}=1.75A	
V_{in}=10V (Buck-Boost Mode)		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
		(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)
V_{in}=20V (Buck Mode)		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
		(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)

Inductor:
H_1-H_3 **shorted** → $L=L_1$ (10µH, 1.86mΩ)
H_2-H_3 **shorted** → $L=L_2$ (3.3µH, 1.86mΩ)

Sensing resistor:
H_4-H_5 **sh**→ R_s = 7.5mΩ
H_4-H_5 **op** → R_s = 15mΩ

Switching frequency:
J_{15} **open** → f_s = 150kHz
J_{15} **shorted** → f_s = 300kHz

MOSFETs Q_1 and Q_2:
R_{ds}=17mΩ, Q_{gsw}=4.7nC, Q_g=14nC,
V_{th}=3V, R_{gint}=13Ω, g_{FS}=62S

LM5118 MOSFETs gate driver:
V_{dr}=7V, R_{dr}=3Ω
Diodes D_1 and D_2:
V_f=0.8V

Answer:

1 Are the losses at higher switching frequency higher than at low switching frequency?

☐ yes ☐ no ☐ it depends on line voltage ☐ it depends on load current ☐ other: ______________

2 For a given load current, are the losses higher in Buck Mode operation or in Buck-Boost Mode operation?

☐ higher in BM ☐ higher in BBM ☐ it depends on load current ☐ it depends on switching frequency ☐ other: ______________

3 For a given input voltage, do the losses increase with the load current?

☐ they increase ☐ they decrease ☐ it depends on switching frequency ☐ it depends on BM/BBM operation ☐ other: ______________

Test#2: preparation and procedure

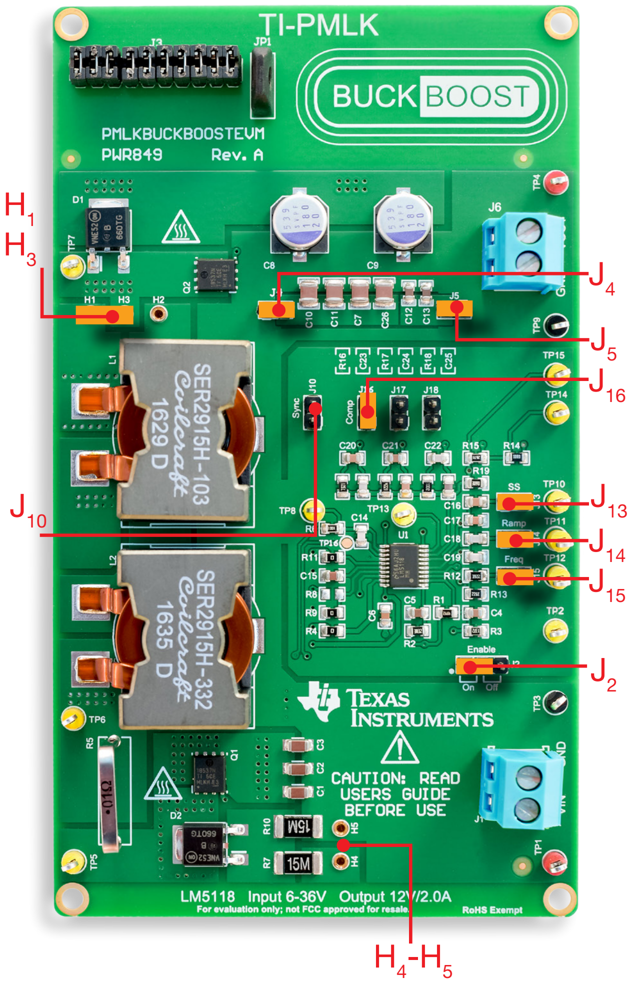


Figure 5. LM5118 board: jumpers set-up for Test#2

Initial jumpers set-up (see Figure 5):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start capacitors connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the MULTIMETER and set DC VOLTAGE MODE
2) turn on the OSCILLOSCOPE, set CH-1 in DC 50Ω coupling mode, set CH-2 and CH-3 in DC 1MΩ coupling mode, select CH-2 as trigger source, and execute the “de-gauss” of the current probe to remove dc bias
3) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
4) turn on the ELECTRONIC LOAD (with LOAD ON button OFF), set the CONSTANT CURRENT MODE, and set the current at 0.2A
5) turn ON the POWER SUPPLY “OUT ON” button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0A in the ELECTRONIC LOAD display, and a very small value in the DC POWER SUPPLY current display (if you do read values different than as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
6) turn ON the ELECTRONIC LOAD ON button and adjust the DC POWER SUPPLY knob until you read 10V in the DC POWER SUPPLY voltage display. In these conditions you should read about 12V in the MULTIMETER display, 0.2A in the ELECTRONIC LOAD display, 0.24A in the DC POWER SUPPLY current display. On CH-1 of the OSCILLOSCOPE you should and see a weveform with triangular impulses separated by intervals with oscillations, and waveforms with square impulses on CH-2 (zero to V_{in}) and CH-3 (zero to V_{out}), separated by intervals with oscillations (if the values you read and the waveforms you see do not look as described above, turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY and verify the experiment setup)
7) read the average input voltage value on the DC POWER SUPPLY voltage display, the average output voltage value on the MULTIMETER display, the average input current in the DC POWER SUPPLY current display and the average output current in the ELECTRONIC LOAD display
8) watch the inductor current waveform on CH-1 of the OSCILLOSCOPE to assess whether the regulator is operating in CCM or DCM, measure the peak, the valley and the average value of the inductor current, measure the frequency and duty-cycle of the Buck switching node voltage (watch the time when the voltage equals V_{in}) on CH-2 of the OSCILLOSCOPE, and use these values according to *Measure and Calculate* section instructions. Repeat this step for all the load current and input voltage values listed in Table 2
9) turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, remove the jumper shorting H_1-H_3, short H_2-H_3 to setup the inductance $L = 3.3µH$ and repeat steps from 3) to 8)
10) at the end of the measurements, turn OFF the ELECTRONIC LOAD “LOAD ON” button and the DC POWER SUPPLY “OUT ON” button, then switch off all the instruments.

Test#2: measure and calculate

For the operating conditions of Table 2:

1) Measure the average input voltage V_{in}, input current I_{in}, output voltage V_{out} and output current I_{out}, the switching frequency f_s, the duty-cycle D, the peak and valley values I_{pk} and I_{vl} of the inductor current
2) assess whether the regulator operates in CCM or DCM by observing the inductor current (in CCM operation the valley current I_{vl} at the beginning of the switching cycle is positive) (*see also Experiment 1*)
3) based on the CCM/DCM assessment, and on the BM/BBM operation, use the appropriate formulae provided in the *Theory Background* section to calculate the power losses of MOSFETs, diodes, inductor and sensing resistance, then calculate the experimental total power losses $P_{exp} = P_{in} - P_{out} = V_{in}I_{in} - V_{out}I_{out}$ and report the result in Table 2.

Table 2 Power losses of the Buck-Boost converter at V_{in} = 10V and V_{in} = 20V, with f_s = 300kHz, at different load contitions and with different inductor setup

Ind. Cond. [mW] (1); sens. resit. [mW] (2); FET Cond. [mW] (3); FET Swit. [mW] (4); (5) P_{exp} [mW]		Load current																								
		I_{out}=0.2A					I_{out}=0.4A					I_{out}=0.6A					I_{out}=0.8A					I_{out}=1.0A				
L 10µH	V_{in} = 10V	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
	V_{in} = 20V	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
L 3.3µH	V_{in} = 10V	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
	V_{in} = 20V	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)

Inductor:
H_1-H_3 **shorted** → L=L_1 (10µH, 1.86mΩ)
H_2-H_3 **shorted** → L=L_2 (3.3µH, 1.86mΩ)

Sensing resistor:
H_4-H_5 **sh**→ R_s = 7.5mΩ
H_4-H_5 **op** → R_s = 15mΩ

Switching frequency:
J_{15} **open** → f_s = 150kHz
J_{15} **shorted** → f_s = 300kHz

MOSFETs Q_1 and Q_2:
R_{ds}=17mΩ, Q_{gsw}=4.7nC, Q_g=14nC,
V_{th}=3V, R_{gint}=13Ω, g_{FS}=62S

LM5118 MOSFETs gate driver:
V_{dr}=7V, R_{dr}=3Ω
diodes D_1 and D_2:
V_f=0.8V

Answer:

1 How do the calculated losses change while the inductance decreases?

inductor, conduction:	☐ they increase	☐ they decrease	☐ it depends on the load current/input voltage	☐ other: ______
MOSFETs, conduction:	☐ they increase	☐ they decrease	☐ it depends on the load current/input voltage	☐ other: ______
MOSFETs, switching:	☐ they increase	☐ they decrease	☐ it depends on the load current/input voltage	☐ other: ______
MOSFETs, gate:	☐ they increase	☐ they decrease	☐ it depends on the load current/input voltage	☐ other: ______

2 How does the measured power losses change while the inductance decreases?

☐ it increases ☐ it decreases ☐ it depends on the load current/input voltage ☐ other: ______

3 Which are is the component determining the prevalent contribution to power losses?

☐ the diodes ☐ the MOSFETs ☐ the inductor ☐ it depends on the load current/input voltage ☐ other: ______

Discussion

In Test#1 we are interested in detecting the CCM/DCM operation mode and evaluating power losses of a Buck-Boost regulator, at different input voltage, load current and frequency.

The *Theory Background* section highlights that the power losses of the Buck-Boost converter depends on the input voltage V_{in}, the switching frequency f_s, the load current I_{out}, and the inductance L. For a given input voltage, switching frequency and inductance, the Buck-Boost converter can operate in DCM or in CCM depending on the load current. In particular, the DCM can be observed when the load current I_{out} is lower than the value of the threshold current I_{dcm} given by formulae (3) and (6) in the *Theory Background* section of *Experiment #1*, for Buck Mode (BM) and for Buck-Boost Mode (BBM) operation respectively. Therefore, as highlighted in the *Theory Background* section, depending on the input voltage value, we have four possible operation mode combinations: BM-CCM, BM-DCM, BBM-CCM and BBM-DCM. Let us analyze separately the main impact of BM vs BBM and the main impact of CCM vs DCM on losses.

The BM vs BBM operation impacts the contribution of MOSFETs and diodes to power losses.

During the BM operation, the MOSFET Q_2 is permanently OFF, whereas the diode D_2 is permanently ON. Therefore, there is no contribution to losses by the MOSFET Q_2, while the losses of diode D_2 dominate, due to the forward voltage drop. The conduction losses of MOSFET Q_1 are much smaller than the conduction losses of the diode D_1, as the 17mΩ MOSFET channel resistance R_{ds} determines a drain-to-source voltage drop V_{ds} which is much smaller than the Schottky diode voltage drop V_f. The switching losses of MOSFET Q_1 during BM operation are proportional to the load current. During BBM operation, the loss contribution is influenced by the synchronous commutations of the pairs Q_1-D_1 and Q_2-D_2. The two diodes operate in series when they are turned ON and hence the losses are two times the losses of each diode. The total conduction and gate losses of the MOSFETs Q_1 and Q_2 are twice the losses of the single MOSFET, as the two devices are identical. The switching losses of the two MOSFETs Q_1 and Q_2 are however different. The MOSFET Q_1 operates as the high-side FET of the Buck converter. Hence, Q_1 switching losses are proportional to input voltage V_{in} (see the *Theory Background* section of *Experiment 1* in *TI-PMLK Buck Experiment Book [13]*). The switching losses of the MOSFET Q_2, instead, are proportional to the output voltage V_{out}, as it operates as the low-side FET of the boost converter (see the *Theory Background* section of *Experiment 2* in *TI-PMLK Boost Experiment Book [12]*). The inductor in the LM5118 Buck-Boost converter has a very small winding resistance, about 1.9mΩ, so that its conduction losses are quite small compared to diodes and MOSFETs.

The CCM vs DCM operation impacts the MOSFETs switching losses.

When the converter operates in CCM, there are switching losses both when the MOSFETs turn ON and turn OFF. During DCM, the switching losses when the MOSFETs turn ON are negligible, because the commutation occurs at zero current level. In fact, in DCM the inductor current falls to zero before the end of the switching period and remains at zero during the dead interval, up to the start of the next switching period due to the diodes interdiction. (*see the discussion of Experiment 1 on the real behavior of inductor current and switching node voltage in DCM*). This is why we have in the *Theory Background* section different formulae for inductor winding losses in CCM and DCM operation. The conduction losses of MOSFETs are also different when the boost converters operates in DCM. In fact, due to the different values of peak and valley of the inductor currents I_{pk} and I_{vl}, the MOSFETs rms currents change. The increase of the switching frequency causes a decrease of the conduction losses and an increase of the switching losses. The increase of switching losses is determined by two effects: the higher rate of commutations per unit of time, and the increase of MOSFETs commutation times due to the decrease of ripple (see discussion of *Test#2* below).

In Test#2 we are interested in analyzing the impact of the inductor on the power losses of the Buck-Boost regulator, at different input voltage and load current.

The formulae provided in the *Theory Background* section show that a lower inductance increases the peak-to-peak inductor ripple current in CCM, the load current threshold for DCM operation, and the peak inductor current ripple in DCM. The increase of the inductor peak-to-peak ripple current in CCM and of the peak inductor current in DCM involve an increase of the conduction losses of the MOSFETs, the diodes, the inductor and the sensing resistor. The increase of the inductor peak-to-peak ripple current determines a lower valley current I_{vl} in CCM, which results in shorter MOSFET turn ON time t_{ON}, and a higher peak current I_{pk} in CCM and DCM, which results in a shorter MOSFET turn OFF time t_{OFF}. As a consequence, the switching losses can increase or decrease depending on the resulting value of $I_{vl}t_{ON}+I_{pk}t_{OFF}$, which is determined by the combination of values of the MOSFETs gate-to-source threshold voltage V_{th}, transconductance g_{fs}, switching gate charge Q_{gsw}, internal gate resistance R_{gint}, and by gate driver voltage V_{dr} and resistance R_{dr}.

Experimental plots

The plots collected in the Figures 6 to 9 show the inductor current and the switching nodes voltage of the LM5118 Buck-Boost regulator in different setup and operating conditions.

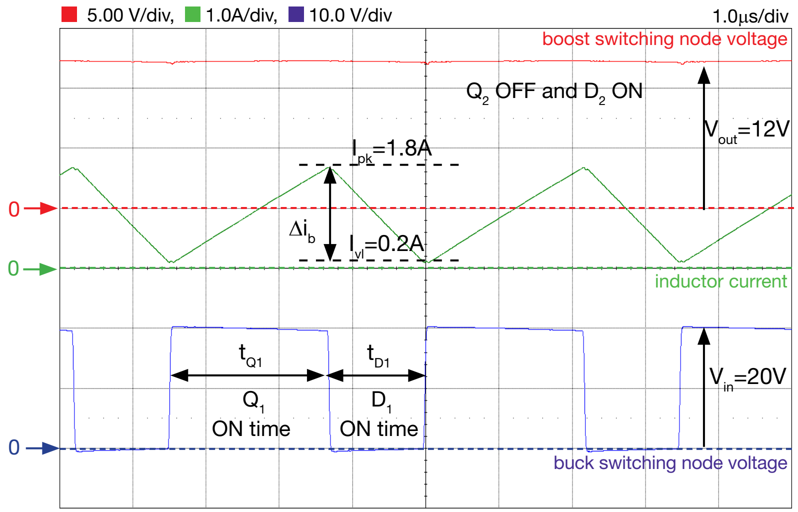


Figure 6. LM5118 regulator in steady-state CCM Buck-Boost operation: V_{in}=20V, I_{out}=1.0A, f_s=300kHz, L=10µH

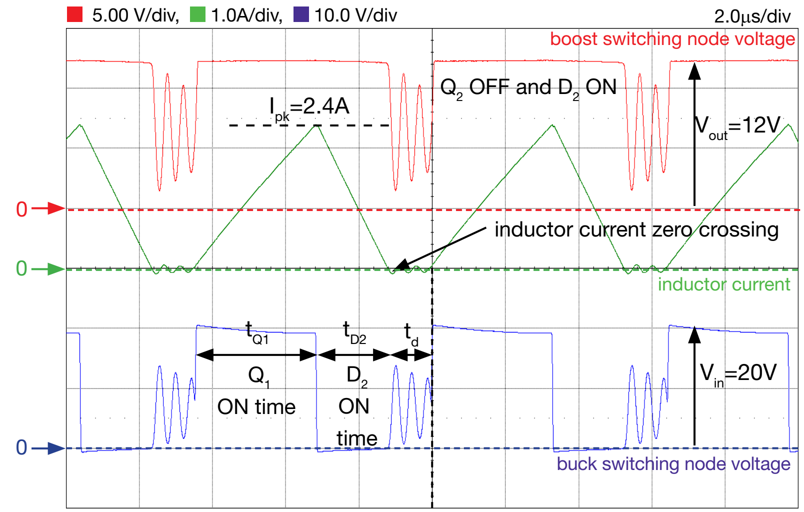


Figure 7. LM5118 regulator in steady-state CCM Buck operation: V_{in}=20V, I_{out}=1.0A, f_s=150kHz, L=10µH

Figures 6 and 7 highlight the difference between the waveforms of the LM5118 Buck-Boost regulator in steady-state CCM Buck Mode operation (Figure 6) and in steady-state DCM Buck Mode operation (Figure 7). The difference in CCM/DCM operation mode is determined by the decrease of the switching frequency from 300kHz to 150kHz. You can observe that the peak-to-peak inductor current ripple in CCM operation (Figure 6) is about 1.6A, with valley current value I_{vl}=0.2A and peak current value I_{pk}=1.8A, whereas in DCM operation (Figure 7) the peak current value rises to 2.4A and the valley current value is zero. These differences impact the overall power losses and in particular the conduction and switching losses of MOSFETs, as explained in the *Discussion* section. You can observe that the voltage of the output side switching node (boost) is flat in CCM operation (Figure 6). In DCM, you can see oscillations during the dead time interval on both the input and the output side switching node voltages (Figure 7). This is due to the resonance loop formed by the inductor and the parasitic capacitances associated with the MOSFETs and diodes. Indeed, also the diode D_2 turns OFF during the dead interval, after the inductor current zero crossing instant highlighted in Figure 7.

Experimental plots

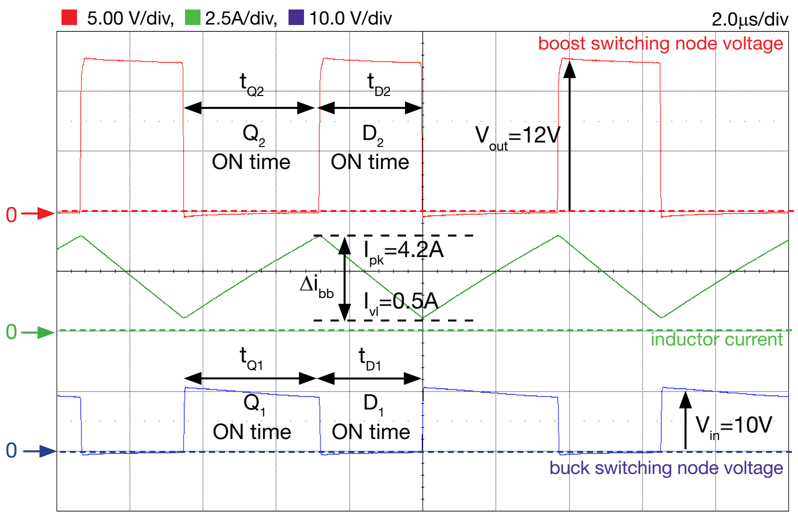


Figure 8. LM5118 regulator in steady-state CCM Buck-Boost operation: V_{in}=10V, I_{out}=1.0A, f_s=150kHz, L=10µH

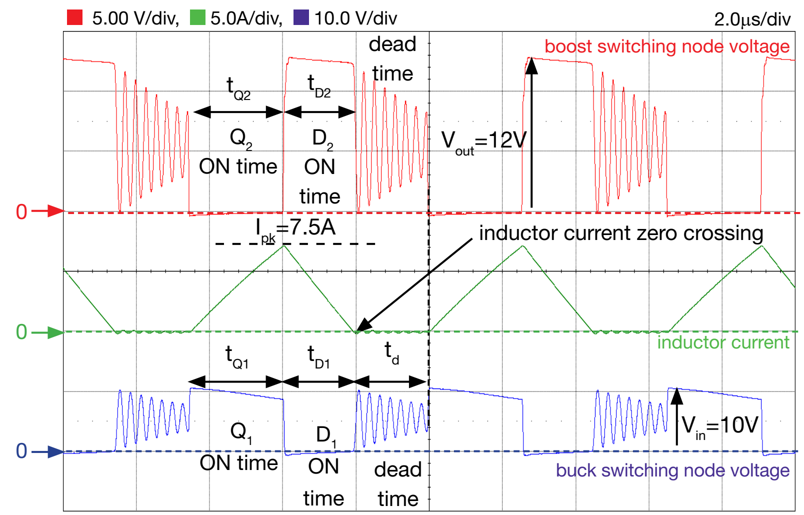


Figure 9. LM5118 regulator in steady-state DCM Buck-Boost operation: V_{in}=10V, I_{out}=1.0A, f_s=150kHz, L=3.3µH

Figures 8 and 9 highlight the difference between the waveforms of the LM5118 regulator in steady-state CCM Buck-Boost Mode operation (Figure 8) and in steady-state DCM Buck-Boost Mode operation (Figure 9). The difference is determined by the decrease of the inductance from 10µH to 3.3µH. You can observe that the peak-to-peak inductor current ripple in CCM operation (Figure 8) is about 3.7A, with valley current value I_{vl}=0.5A and peak current value I_{pk}=4.2A, whereas in DCM operation (Figure 9) the peak current value rises to 7.5A and the valley current value is zero. These differences impact the overall power losses, as explained in the *Discussion* section. You can also observe that the voltage of the output side switching node (boost) during the D_2 ON time t_{D2} is not flat. The decrease of the output side switching node voltage is determined by the reduction of the diode D_2 forward voltage while the inductor current falls from 4.2A down to 0.5A in CCM (Figure 8) and from 7.5A down to zero in DCM (figure (9). Similarly, the input side switching node voltage (Buck) during the Q_1 ON time t_{Q1} is not flat, as the drain-to-source MOSFET voltage $V_{ds} = R_{ds} i_L(t)$ increases while the inductor current rises from 0.5A up to 4.2A in CCM (Figure 8) and from zero up to 7.5A in DCM (figure 9). Moreover, you can see that the average, valley and peak values of the inductor current show some difference with respect the theoretical values obtained by using the formulae provided in the *Theory Background* section. This difference is the effect of losses, which cause a change in the real value of the duty-cycle. Dividing the theoretical duty-cycle by the efficiency provides a more realistic value.

Experiment 3

The goal of this experiment is to analyze how the input voltage, the load current and the feedback compensation influence the dynamic performances of the Buck-Boost regulator.

Case Study

The goal of this experiment is to analyze the influence of input voltage, load current and feedback compensation on the dynamic response of the Buck-Boost regulator.

The TI-PMLK LM5118 Buck-Boost regulator operates with V_{in}=[6,36]V[(1)], while regulating the output voltage at the nominal value V_{out}=12V in the load current range I_{out}=[0,3]A. Fig.1 shows the simplified circuit schematic of the regulator including the main external power and control components and the internal architecture of the LM5118 IC. The LM5118 implements an emulated current mode control. The internal emulated current ramp generator injects a current into the external ramp capacitor, whose magnitude depends on input and output voltages and on Buck Mode (BM) or BuckBoost Mode (BBM) operation. BM and BBM are operated by the IC based on input voltage level (see *Experiment #1* and *Experiment #2*). The ramp capacitor emulates the inductor current ramp in the first part of the switching period. For exact current emulation, the capacitance must fulfill the condition $C_{ramp}=g_m L/A_s$, where L is the inductance, A_s is the current sensing gain and g_m is the transconductance of the ramp generator. Changing C_{ramp} capacitance has the equivalent effect of changing the sensing gain A_s. In the low frequency range, the emulated currrent mode control simplifies the dynamic behavior of the converter, as it makes the inductor current variations proportional to the variations of the control signal V_c generated by the feedback error amplifier. This allows easy dynamic modeling and feedback compensation design.

[(1)] Restricted range adopted for this educational board, compared to the 3V to 75V full range of LM5118 [5]

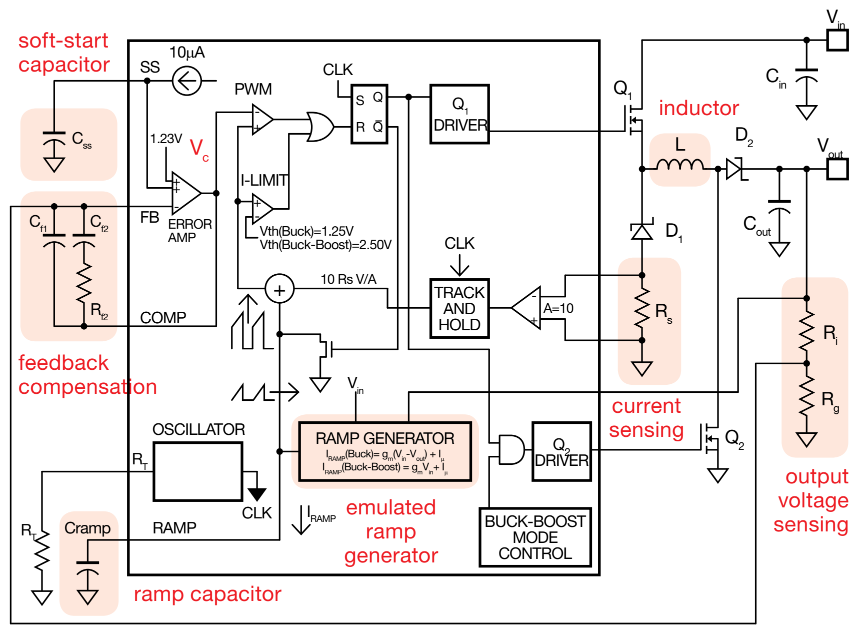


Figure 1. Simplified schematic of the LM5118 Buck-Boost regulator

Test#1. We set-up the LM5118 Buck boost regulator with different input voltage values and we observe the load transient response. The expectation is that, after each load current change, the output voltage has some transient surge and then it returns to the nominal value. The magnitude of the output voltage transient surges is measured. The influence of the BM and BBM operation and of the feedback compensation setup on the magnitude of voltage transient surges is observed and discussed.

Test#2. We observe the impact of the inductance on the load transient response of the LM5118 Buck-booct regulator. The magnitude of the output voltage transient surges is measured. The influence of the feedback compensation setup on the magnitude of voltage transient surges is observed and discussed.

Experiment 3

Theory Background

The fundamentals for the frequency analysis of the emulated peak current mode controlled Buck-Boost converter in CCM are summarized in the following equations. *(see [1]-[4] for more details on Buck-Boost topology operation, dynamic modeling and current-mode control analysis and design; see [5] for more details on LM5118 regulator operation and features)*

The simplified voltage feedback loop gain in **Buck-Boost Mode** is:

$$T_u(s) \cong T_{u0} \frac{\left[1+\frac{s}{\omega_{ESR}}\right]\left[1-\frac{s}{\omega_{RHP}}\right]}{\left[1+\frac{s}{\omega_{LFP}}\right]\left[1+\frac{s}{\omega_{HFP}}\right]}$$

$$T_{u0} = \frac{D'V_{out}}{(1+D)I_{out}A_s}$$

$$\omega_{LFP} = \frac{(1+D)I_{out}}{V_{out}C_{out}}$$

$$C_{out} = C_{cer} + C_{el}$$

$$\omega_{RHP} = \frac{D'^2 V_{out}}{D I_{out} L} \; ; \; D = \frac{V_{out}}{V_{in}+V_{out}}$$

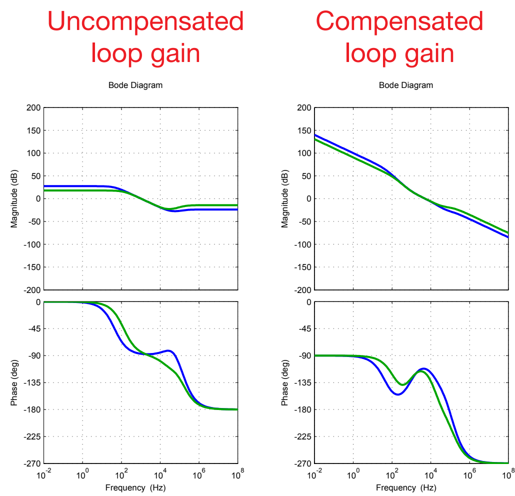
$$^{(*)}\omega_{HFP} = \frac{1}{C_{cer}}\left[\frac{1}{R^*}+\frac{1}{ESR^*}\right]$$

$$R^* = \frac{V_{in}+2V_{out}}{I_{out}}$$

$$ESR^* = \frac{C_{cer}}{C_{out}} ESR$$

(*) the high frequency pole ω_{HFP} can be ignored if the capacitance C_{cer} is much smaller than the capacitance C_{el}.

Figure 2 shows the uncompensated and compensated voltage loop gain in **Buck-Boost Mode** operation (see *Experiment 4* for details on criteria and formulae relevant to the feedback compensation design).



(a) (b)

Figure 2: LM5118 loop gain in Buck-Boost Mode with inductance L = 10µH (H_1-H_3 shorted) and feedback compensation R_{18}, C_{22}, C_{25} connected (jumper J_{18} shorted), providing about 5kHz cross over frequency: green lines: V_{in}=10V@I_{out}=2A, blue lines: V_{in}=10V@I_{out}=1A.

The simplified voltage feedback loop gain in **Buck Mode** is:

$$T_u(s) \cong T_{u0} \frac{\left[1+\frac{s}{\omega_{ESR}}\right]}{\left[1+\frac{s}{\omega_{LFP}}\right]\left[1+\frac{s}{\omega_{HFP}}\right]}$$

$$T_{u0} = \frac{V_{out}}{I_{out}A_s}$$

$$\omega_{LFP} = \frac{I_{out}}{V_{out}C_{out}}$$

$$C_{out} = C_{cer} + C_{el}$$

$$D = \frac{V_{out}}{V_{in}}$$

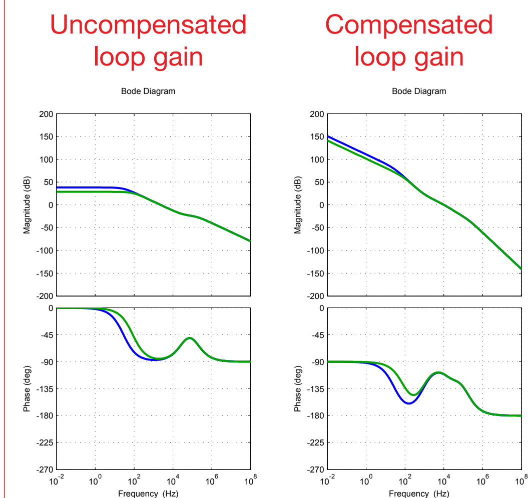
$$^{(*)}\omega_{HFP} = \frac{1}{C_{cer}}\left[\frac{1}{R^*}+\frac{1}{ESR^*}\right]$$

$$R^* = \frac{V_{out}}{I_{out}}$$

$$ESR^* = \frac{C_{cer}}{C_{out}} ESR$$

(*) the high frequency pole ω_{HFP} can be ignored if the capacitance C_{cer} is much smaller than the capacitance C_{el}.

Figure 3 shows the uncompensated and compensated voltage loop gain in **Buck Mode** operation (see *Experiment #4* for details on criteria and formulae relevant to the feedback compensation design).



(a) (b)

Figure 3: LM5118 loop gain in Buck Mode with inductance L = 10µH (H_1-H_3 shorted) and feedback compensation R_{18}, C_{22}, C_{25} connected (jumper J_{18} shorted), providing about 10kHz cross over frequency: green lines: V_{in}=20V@I_{out}=2A, blue lines: V_{in}=20V@I_{out}=1A.

Good to know:

❶ Due to the worst case phase lag determined by the RHP zero in Buck-Boost Mode, the three compensators on the board have been designed for Buck-Boost Mode operation at minimum input voltage and maximum load current [V_{in}=6V,I_{out}=3A], to achieve 52° phase margin at: f_c = 2kHz with L = L_1 [J_{16} sh], f_c = 1kHz with L = L_2 [J_{17} sh], f_c = 4kHz with L = L_1 [J_{18} sh]. The cross-over frequency changes with the operating line/load conditions ❷ The Buck-Boost dynamic model in DCM is different (*see [1]-[3] for more details*)

Experiment set-up: configuration

The instruments needed for this experiment are: a DC POWER SUPPLY, an OSCILLOSCOPE and a DC ELECTRONIC LOAD with dynamic current mode capabilities(*) . Figure 4 shows the instruments connections. Follow the instructions provided in next page to set-up the connections.

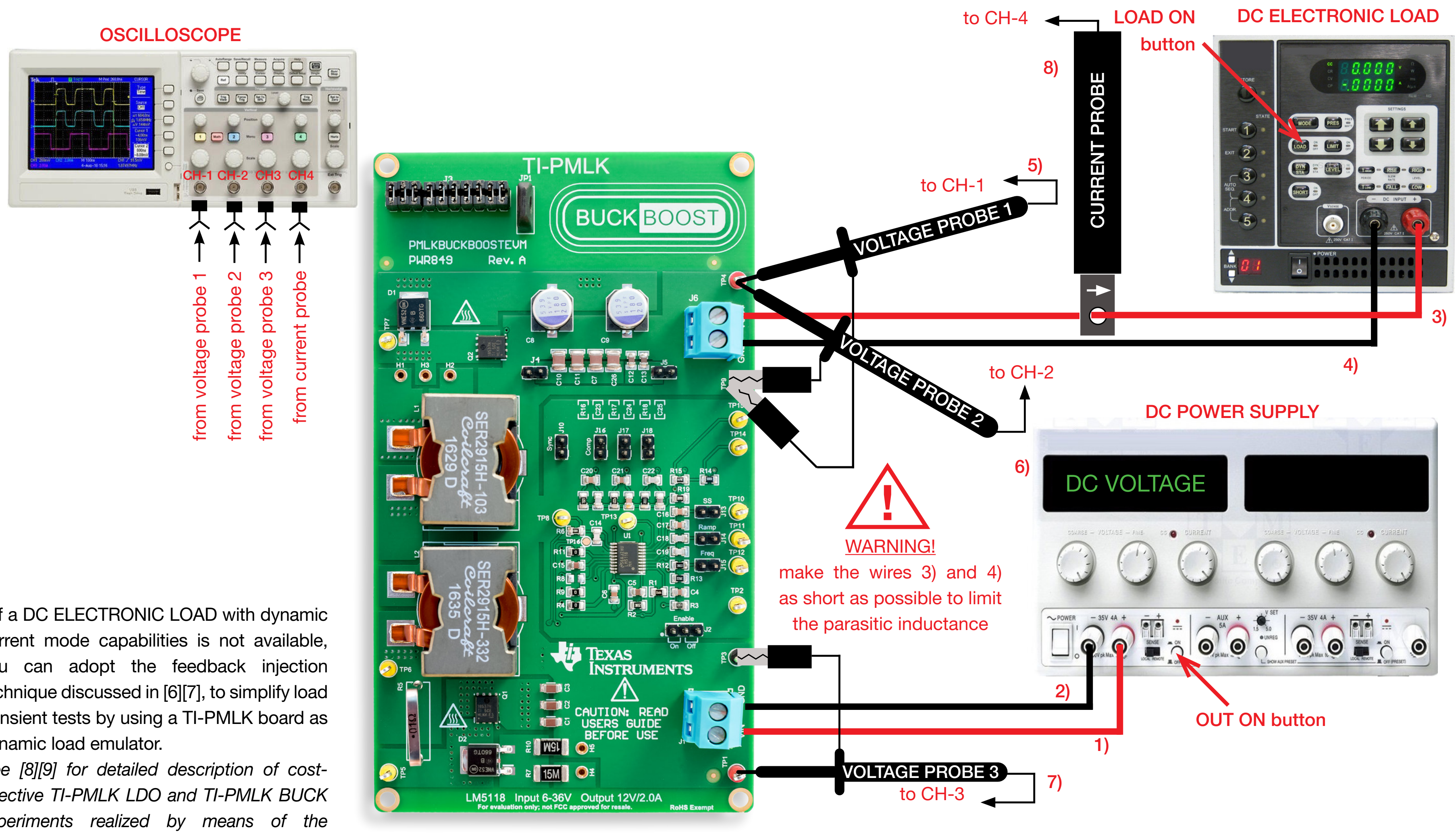


Figure 4. Experiment set-up.

(*) If a DC ELECTRONIC LOAD with dynamic current mode capabilities is not available, you can adopt the feedback injection technique discussed in [6][7], to simplify load transient tests by using a TI-PMLK board as dynamic load emulator.
(see [8][9] for detailed description of cost-effective TI-PMLK LDO and TI-PMLK BUCK experiments realized by means of the feedback injection technique)

Experiment set-up: instructions

With all the instruments turned off, make the following **connections**:

1) connect the POSITIVE (RED) OUTPUT of the DC POWER SUPPLY to the INPUT (VIN) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

2) connect the NEGATIVE (BLACK) OUTPUT of the DC POWER SUPPLY to the GROUND (GND) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

3) connect the OUTPUT (VOUT) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the POSITIVE (RED) INPUT of the ELECTRONIC LOAD

4) connect the GROUND (GND) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the NEGATIVE (BLACK) INPUT of the ELECTRONIC LOAD

5) connect a voltage probe to channel 1 of the oscilloscope and hang it on the TEST PIN TP_4 which is the output voltage of the LM5118 Buck-Boost regulator

6) connect a second voltage probe to channel 2 of the oscilloscope and hang it on the TEST PIN TP_4 which is the output voltage of the LM5118 Buck-Boost regulator

7) connect a voltage probe to channel 3 of the oscilloscope and hang it on the TEST PIN TP_1 which is the input voltage of the LM5118 Buck-Boost regulator

8) connect a current probe to channel 4 of the oscilloscope and hang it on the cable connecting the OUTPUT (VOUT) of the J_6 screw terminal of the LM5118 Buck boost regulator to the POSITIVE (RED) INPUT of the ELECTRONIC LOAD, ensuring that the arrow printed on the probe clamps corresponds to the current that enters the ELECTRONIC LOAD

Test#1: preparation and procedure

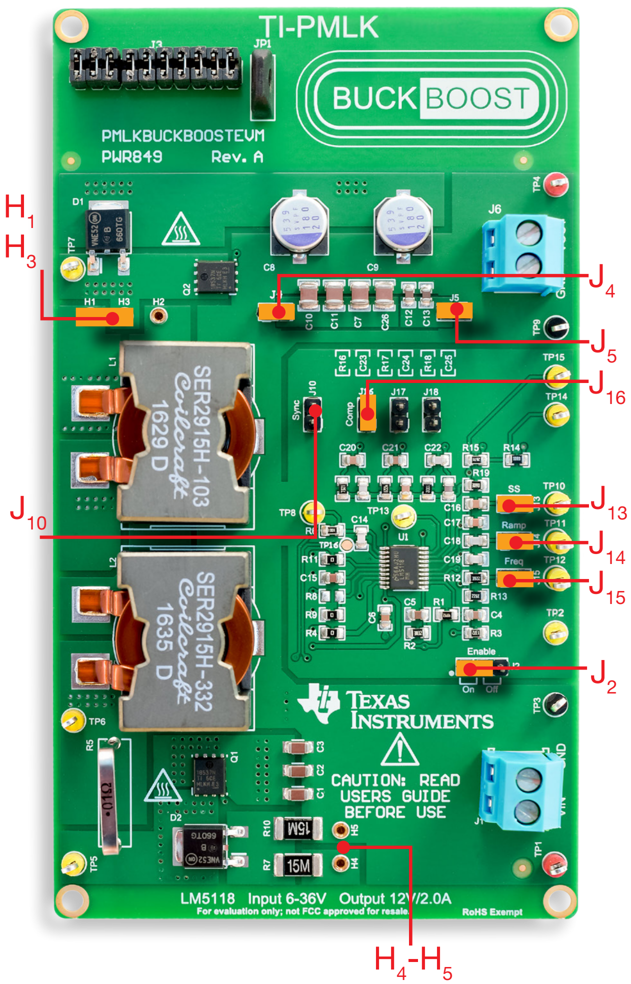


Figure 5. LM5118 board: jumpers set-up for Test#1

Initial jumpers set-up (see Figure 5):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the OSCILLOSCOPE, set CH-1 in DC 1MΩ coupling mode, CH-2 in AC 1MΩ coupling mode and CH-3 in DC 1MΩ coupling mode, set CH-4 in DC 50Ω coupling mode, select CH-4 as trigger source, execute the “de-gauss” of the current probe to remove possible dc bias in the current probe
2) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
3) turn on the ELECTRONIC LOAD (ensure that the “LOAD ON” button is OFF), set the DYNAMIC CURRENT MODE, the low current level at 1A for 4ms, the high current level at 2.0A for 4ms, the current rise and fall slew-rates at the highest level allowed by the instrument
4) turn ON the POWER SUPPLY “OUT ON” button. In these conditions you should see the load current on the CH-4 trace of the OSCILLOSCOPE as a flat waveform at zero level, the DC+AC components of the output voltage on the CH-1 trace as a flat waveform at 12V average value, the AC component of output voltage on CH-2 trace as a flat waveform at zero level, and the input voltage on CH-3 trace as a flat line at 10V level (if the waveforms do not look as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
5) turn ON the ELECTRONIC “LOAD ON” button. In these conditions you should see the load current on the CH-4 trace of the OSCILLOSCOPE as square-wave between 1.0A and 2A, the DC+AC components of the output voltage on the CH-1 trace as a waveform with 12V average value with small positive and negative surges during the rise and fall of the load current, the AC component of output voltage on CH-2 trace as a flat waveform at zero level with small positive and negative surges during the rise and fall of the load current, and the input voltage on CH-3 trace as a flat line at 10V level. (if the waveforms do not look as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
6) record in Table 1 the magnitude of the output voltage surges after each load transient for the input voltage values listed in Table 1 (you do not need to turn OFF the POWER SUPPLY “OUT ON” button while adjusting the input voltage);
7) zoom the inductor current waveform and verify if the Buck-Boost converter operates always in CCM before, during and after each load transient and record the conditions involving DCM operation (see *Experiment 1 Preparation and Procedure* section for instructions on DCM detection)
8) turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, then open the J_{16} jumper to disconnect the R_{16}, C_{20}, C_{23} parts to the error amplifier and short the jumper J_{18} to connect the R_{18}, C_{22}, C_{25} parts to the error amplifier, repeat the steps 4) to 7), and report the results in Table 1
9) at the end of the measurements, turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, then switch off all the instruments

Test#1: measure and calculate

For the operating conditions of Table 1, measure the peak output voltage overshoot and undershoot, following the instructions provided in the preceding *Preparation and Procedure* section, record the occurrence of CCM/DCM operation, report the results in Table 1, and answer the questions.

Table 1. Load transient overshoot and undershoot magnitude of LM5118 Buck boost regulator at f_s = 300kHz, with L = 10µH, for different input voltage and compensation setup.

	case (a): J_{16} sh, J_{17} op, J_{18} op				case (b): J_{16} op, J_{17} op, J_{18} sh			
	(1) ΔV_{out} [mV] 1.0A→2.0A	CCM/DCM	(2) ΔV_{out} [mV] 2.0A→1.0A	CCM/DCM	(1) ΔV_{out} [mV] 1.0A→2.0A	CCM/DCM	(2) ΔV_{out} [mV] 2.0A→1.0A	CCM/DCM
V_{in}=10V	(1)	☐ CCM ☐ DCM	(2)	☐ CCM ☐ DCM	(1)	☐ CCM ☐ DCM	(2)	☐ CCM ☐ DCM
V_{in}=20V	(1)	☐ CCM ☐ DCM	(2)	☐ CCM ☐ DCM	(1)	☐ CCM ☐ DCM	(2)	☐ CCM ☐ DCM

feedback error amplifier compensation				current sensing resistance		emulated ramp capacitor		output voltage divider high-side resistance
	C_{f1}	C_{f2}	R_{f2}	R_s [mΩ]		C_{ramp} [pF]		R_i=2.67kΩ
J_{16} sh [H_1-H_3 sh]	3.3nF	33nF	7.32kΩ	H_4-H_5 op	15	J_{14} op	150	output voltage divider low-side resistance
J_{17} sh [H_2-H_3 sh]	10nF	100nF	4.22kΩ	H_4-H_5 sh	7.5	J_{14} sh	330	R_g=309Ω
J_{18} sh [H_1-H_3 sh]	470pF	22nF	13.3kΩ	inductance		switching frequency		current sensing gain
output capacitor				L [µH]		f_s [kHz]		A_s=10R_s
J_4 op, J_5 op	C_{out} = 2x180µF, 25mΩ(el)			H_1-H_3 sh	10	J_{15} op	150	ramp transconductance and bias
J_4 sh, J_5 sh	C_{out} = 2x180µF, 25mΩ(el)//4x22µF(cer)//2x0.47µF(cer)			H_2-H_3 sh	3.3	J_{15} sh	300	g_m=5µA/V, I_μ=50µA

Answer:

1. Is the load transient voltage overshoot magnitude bigger than the undershoot magnitude? ☐ yes ☐ no ☐ it depends on line voltage

2. Does the converter operate always in CCM ? ☐ yes ☐ no ☐ it depends on line voltage

3. How does the load transient surge magnitude change when the input voltage increases? ☐ it increases with voltage ☐ it decreases with voltage ☐ it is not correlated

4. What is the factor determining the strongest change in the load transient surge magnitude? ☐ the input voltage ☐ the compensation ☐ the DCM operation

Test#2: preparation and procedure

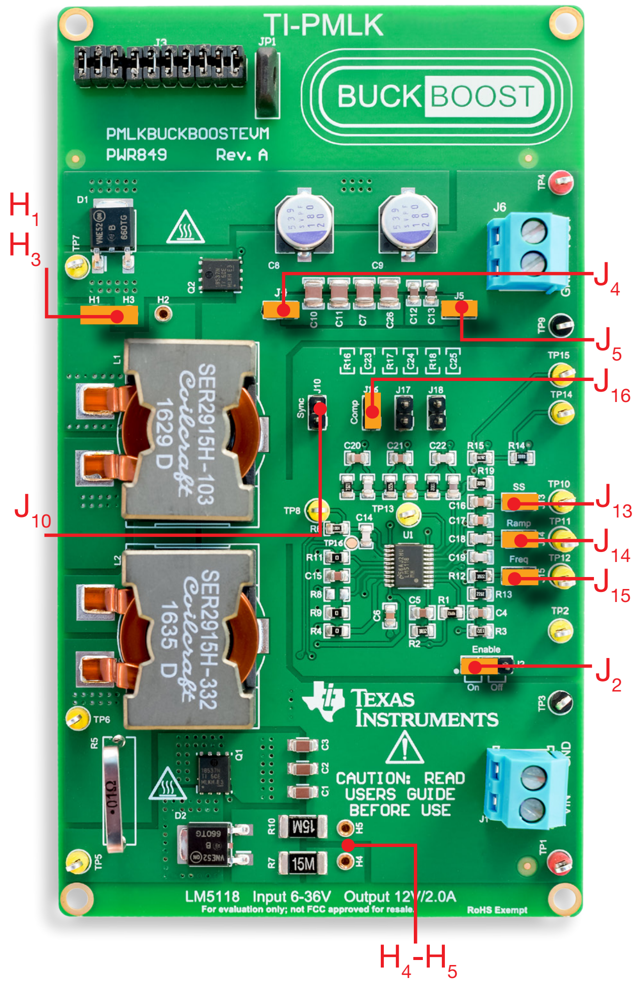


Figure 6. LM5118 board: jumpers set-up for Test#2

Initial jumpers set-up (see Figure 6):

- J_2 **shorted** in **ON** position → regulator enabled
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22µF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.4.7µF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10µH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10µH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the OSCILLOSCOPE, set CH-1 in DC 1MΩ coupling mode, CH-2 in AC 1MΩ coupling mode and CH-3 in DC 1MΩ coupling mode, set CH-4 in DC 50Ω coupling mode, select CH-4 as trigger source, execute the “de-gauss” of the current probe to remove possible dc bias in the current probe
2) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
3) turn on the ELECTRONIC LOAD (ensure that the “LOAD ON” button is OFF), set the DYNAMIC CURRENT MODE, the low current level at 1A for 4ms, the high current level at 1.5A for 4ms, the current rise and fall slew-rates at the highest level allowed by the instrument
4) turn ON the POWER SUPPLY “OUT ON” button. In these conditions you should see the load current on the CH-4 trace of the OSCILLOSCOPE as a flat waveform at zero level, the DC+AC components of the output voltage on the CH-1 trace as a flat waveform at 12V average value, the AC component of output voltage on CH-2 trace as a flat waveform at zero level, and the input voltage on CH-3 trace as a flat line at 10V level (if the waveforms do not look as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
5) turn ON the ELECTRONIC “LOAD ON” button. In these conditions you should see the load current on the CH-4 trace of the OSCILLOSCOPE as square-wave between 1.0A and 1.5A, the DC+AC components of the output voltage on the CH-1 trace as a waveform with 12V average value with small positive and negative surges during the rise and fall of the load current, the AC component of output voltage on CH-2 trace as a flat waveform at zero level with small positive and negative surges during the rise and fall of the load current, and the input voltage on CH-3 trace as a flat line at 10V level. (if the waveforms do not look as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
6) record in Table 1 the magnitude of the output voltage surges after each load transient for the input voltage values listed in Table 1 (you do not need to turn OFF the POWER SUPPLY “OUT ON” button while adjusting the input voltage)
7) zoom the inductor current waveform and verify if the Buck-Boost converter operates always in CCM before, during and after each load transient and record the conditions involving DCM operation (see *Experiment 1 Preparation and Procedure* section for instructions on DCM detection)
8) turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, then open the H_1-H_3 jumper to disconnect the 10µH inductor, short the H_2-H_3 jumper to connect the 3.3µH inductor, open the J_{16} jumper to disconnect the R_{16}, C_{20}, C_{23} parts from the error amplifier and short the jumper J_{17} to connect the R_{17}, C_{21}, C_{24} parts to the error amplifier, repeat the steps 4) to 7), and report the results in Table 1
9) at the end of the measurements, turn OFF the “LOAD ON” button of the ELECTRONIC LOAD and the “OUT ON” button of the DC POWER SUPPLY, then switch off all the instruments

Experiment 3

Test#2: measure and calculate

For the operating conditions of Table 2, measure the peak output voltage overshoot and undershoot, following the instructions provided in the preceding *Preparation and Procedure* section, record the occurrence of CCM/DCM operation, report the results in Table 2, and answer the questions.

Table 2. Load transient overshoot and undershoot magnitude of LM5118 Buck boost regulator at f_s = 300kHz with different inductance, input voltage and compensation setup.

<table>
<tr><td>(1) ΔV_{out} [mV]
1.0A→1.5A</td><td>CCM/DCM</td><td>(2) ΔV_{out} [mV]
1.5A→1.0A</td><td>CCM/DCM</td><td colspan="4">case (a): L=10µH
H_1-H_3 sh, J_{16} sh, J_{17} op, J_{18} op</td><td colspan="4">case (b): L=3.3µH
H_2-H_3 sh, J_{16} op, J_{17} sh, J_{18} op</td></tr>
<tr><td colspan="4">V_{in}=10V</td><td>(1)</td><td>☐ CCM
☐ DCM</td><td>(2)</td><td>☐ CCM
☐ DCM</td><td>(1)</td><td>☐ CCM
☐ DCM</td><td>(2)</td><td>☐ CCM
☐ DCM</td></tr>
<tr><td colspan="4">V_{in}=20V</td><td>(1)</td><td>☐ CCM
☐ DCM</td><td>(2)</td><td>☐ CCM
☐ DCM</td><td>(1)</td><td>☐ CCM
☐ DCM</td><td>(2)</td><td>☐ CCM
☐ DCM</td></tr>
</table>

<table>
<tr><td colspan="4">feedback error amplifier compensation</td><td colspan="2">current sensing resistance</td><td colspan="2">emulated ramp capacitor</td><td>output voltage divider high-side resistance</td></tr>
<tr><td></td><td>C_{f1}</td><td>C_{f2}</td><td>R_{f2}</td><td colspan="2">R_s [mΩ]</td><td colspan="2">C_{ramp} [pF]</td><td>R_i=2.67kΩ</td></tr>
<tr><td>J_{16} sh [H_1-H_3 sh]</td><td>3.3nF</td><td>33nF</td><td>7.32kΩ</td><td>H_4-H_5 op</td><td>15</td><td>J_{14} op</td><td>150</td><td>output voltage divider low-side resistance</td></tr>
<tr><td>J_{17} sh [H_2-H_3] sh</td><td>10nF</td><td>100nF</td><td>4.22kΩ</td><td>H_4-H_5 sh</td><td>7.5</td><td>J_{14} sh</td><td>330</td><td>R_g=309Ω</td></tr>
<tr><td>J_{18} sh [H_1-H_3] sh</td><td>470pF</td><td>22nF</td><td>13.3kΩ</td><td colspan="2">inductance</td><td colspan="2">switching frequency</td><td>current sensing gain</td></tr>
<tr><td colspan="4">output capacitor</td><td colspan="2">L [µH]</td><td colspan="2">f_s [kHz]</td><td>A_s=10R_s</td></tr>
<tr><td>J_4 op, J_5 op</td><td colspan="3">C_{out} = 2x180µF, 25mΩ(el)</td><td>H_1-H_3 sh</td><td>10</td><td>J_{15} op</td><td>150</td><td>ramp transconductance and bias</td></tr>
<tr><td>J_4 sh, J_5 sh</td><td colspan="3">C_{out} = 2x180µF, 25mΩ(el)//4x22µF(cer)//2x0.47µF(cer)</td><td>H_2-H_3 sh</td><td>3.3</td><td>J_{15} sh</td><td>300</td><td>g_m=5µA/V, I_μ=50µA</td></tr>
</table>

Answer:

1. Is the line transient voltage overshoot magnitude bigger with L=10µH or with L=3.3µH? ☐ bigger with L=10µH ☐ bigger with L=3.3µH ☐ it depends on input voltage

2. Does the converter operate always in CCM? ☐ yes ☐ DCM with L=10µH ☐ DCM with L=3.3µH ☐ DCM at V_{in}=10V ☐ DCM at V_{in}=20V

3. How does the load transient surge magnitude change when the input voltage increases? ☐ it increases with voltage ☐ it decreases with voltage ☐ it depends on the inductance

4. What is the factor determining the strongest change in the load transient surge magnitude? ☐ the inductance ☐ the input voltage ☐ the DCM operation

Discussion

In Test#1 we are interested in investigating correlations among the load transient response of the Buck-Boost regulator and the setup of feedback compensation.

A voltage regulator with a good load transient response yields a small output voltage surge when the load current suddenly steps up or steps down. Typical specifications for real world dc-dc power supplies require that the load transient surges are limited within about ±5% of the average output nominal voltage. A simple concept can be applied to quickly assess the impact of any physical or operating parameter on the load transient performance of a voltage regulator: the magnitude of load transient surges decreases if the voltage loop cross-over frequency increases. In fact, a higher cross-over frequency improves the reactivity to load changes of the control voltage v_c generated by the error amplifier (*see Figure 1*). This results in a faster response of the inductor current to the load demand, thus shortening the duration of the time interval wherein the output capacitor has to sustain the unbalance between the inductor current and the load current (*see the TI-PMLK BUCK Experiment Book and TI-PMLK LDO Experiment Book for more insight on load transient issues*). The cross-over frequency and the load transient response of the emulated peak-current control LM5118 Buck-Boost regulator are influenced by three main elements: (a) the inherent dynamic properties of the converter in the Buck Mode (operated at V_{in}=20V) and in the Buck-Boost Mode (operated at V_{in}=10V), (b) the setup of the peak current control loop (which is fixed in this Test#1), and (c) the setup of the voltage feedback compensation. The combination of these elements determines the capability of the Buck-Boost regulator to reject the effects of a load perturbation on the output voltage. Regarding the point (a), the formulae and Bode plots of the loop gain provided in the *Theory Background* section show that when the LM5118 regulator operates in Buck Mode with V_{in}=20V and I_{out}=1A-2A, its loop gain has a higher cross-over frequency (about 10kHz) compared to the Buck-Boost Mode (about 5kHz) with V_{in}=10V and I_{out}=1A-2A. Indeed, the feedback error amplifier gain of the TI-PMLK LM5118 board has been designed for the worst case of Buck-Boost Mode operation, where the RHP zero ω_{RHP} introduces a gain attenuation and a phase lag in the uncompensated loop gain (see Figure 2). In the Buck Mode uncompensated loop gain there is no RHP zero (see Figure 3), the error amplifier determines a higher crossover frequency and higher phase margin in the Buck Mode than in the Buck-Boost Mode. This can motivate the better Buck Mode load transient performance.

[**NOTE:** Given the voltage loop gain T, the cross-over frequency ω_c is the frequency such that the loop gain magnitude equals unity, that is $|T(\omega_c)|=1$. An explicit formula for ω_c is not available. The cross-over frequency ω_c can be determined by means of MATLAB®[10]. If the loop gain transfer function T is not available, it can be measured by means of a network vector analyzer [11] using the 10Ω injection resistor R_{14} mounted in the LM5118 board]

In Test#2 we are interested in investigating correlations among the inductance and the load transient response of the Buck-Boost regulator.

The Test#2 is realized with two different inductances L_1 = 10µH and L_2 = 3.3µH, with the same input voltage and load transient conditions. The simplified low-frequency formulae of voltage loop gain provided in the *Theory Background* section show that, when the LM5118 regulator operates in Buck Mode, with V_{in}=20V, the inductance does not impact directly the feedback loop gain [(*)]. In Buck-Boost Mode, instead, the inductance influences the frequency of the the RHP zero ω_{RHP}, which introduces a gain attenuation and a phase lag in the uncompensated loop gain (see Figure 2). A lower inductance has in principle a beneficial effect on the dynamic performances in Buck-Boost Mode, as it leads the RHP zero to higher frequency. In theTest#2, a specific feedback compensation is adopted for each inductance, providing almost the same cross-over frequency. In this way, the overall effects of the change of the inductance in the compensated voltage loop gain are almost balanced, so that the load transient response with the two inductors is not much different.

[(*)] detailed dynamic models of peak current model control show how the inductance influences the current loop gain (see [1]-[4] for more insight)

Experimental plots

The plots collected in the Figures 7 to 14 show some examples of load transient response of the LM5118 Buck-Boost regulator.

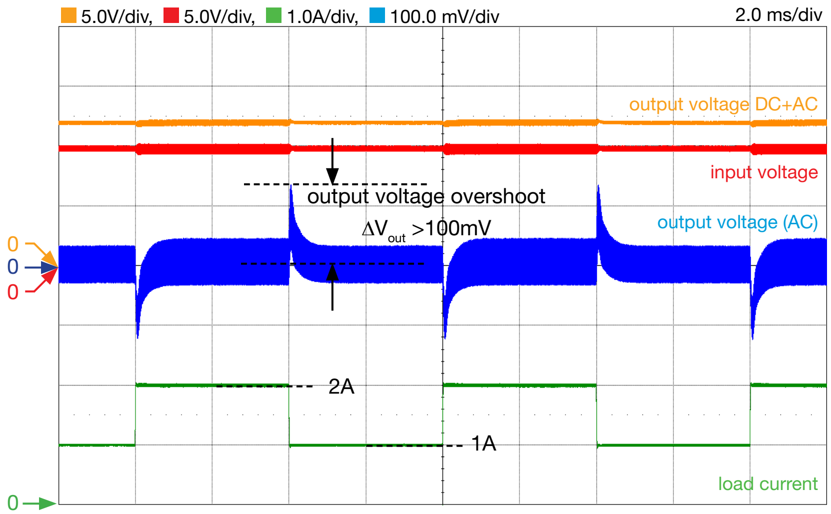


Figure 7. LM5118 bock-boost regulator load transient response in BBM, with R_{16}, C_{20}, C_{23} connected (lower cross-over frequency): V_{in}=10V, I_{out}=1.0A to 2.0A, f_s=300kHz, L=10μH

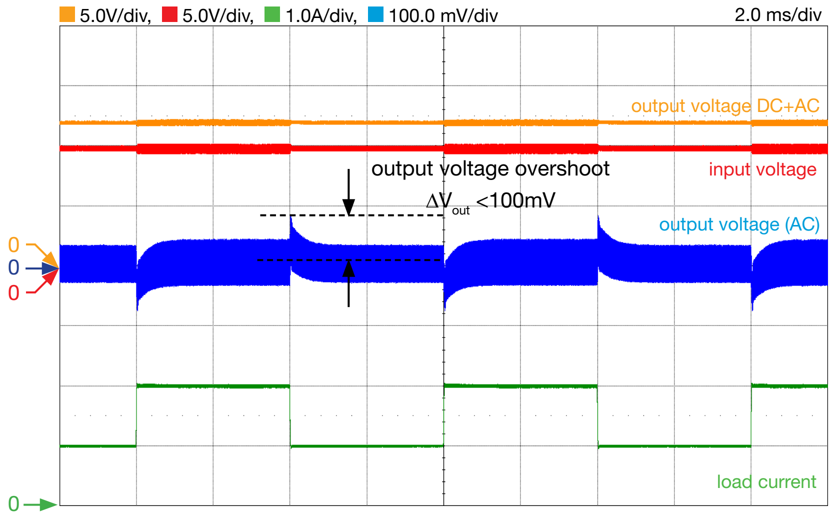


Figure 8. LM5118 bock-boost regulator load transient response in BBM, with R_{18}, C_{22}, C_{25} connected (higher cross-over frequency): V_{in}=10V, I_{out}=1.0A to 2.0A, f_s=300kHz, L=10μH

The plots of Figures 7 and 8 highlight the influence of the voltage feedback error amplifier setup and on the load transient response of the Buck-Boost regulator in Buck-Boost Mode. In Figure 7 you see that the magnitude of output voltage surge during the load trasients exceeds 100mV, with lower cross-over error amplifier setup. In Figure 8, instead, you see that the magnitude of output voltage surge during the load trasients is lower than 100mV, with higher cross-over error amplifier setup.

[NOTE: the acquisitions shown in Figures 7 to 14 have been realized with a digital oscilloscope, by setting the sampling rate at 500MS/s and applying a +2bits digital filtering to the waveforms, in order to reduce the magnitude of the visible ripple at the switching frequency. This allows to better visualize the effects of the load transients on the average value of the output voltage]

Experimental plots

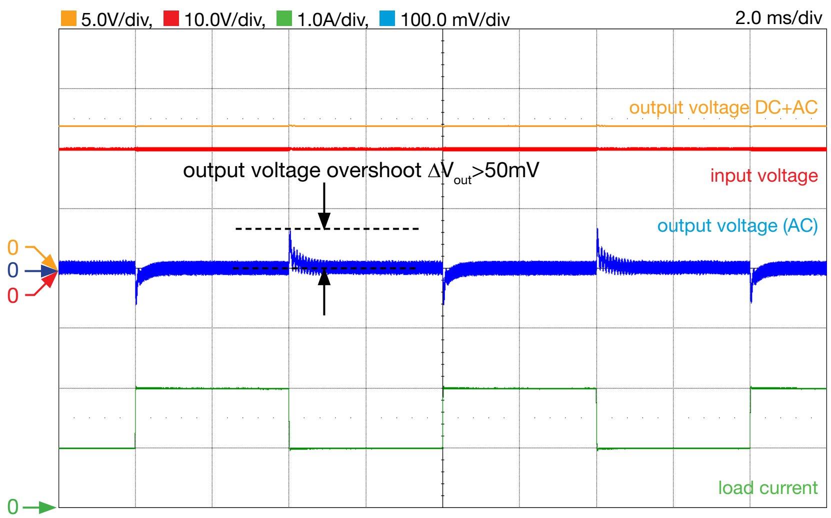


Figure 9. LM5118 Buck-Boost regulator load transient response in BM, with R_{16}, C_{20}, C_{23} connected (lower cross-over frequency): V_{in}=20V, I_{out}=1.0A to 2.0A, f_s=300kHz, L=10µH

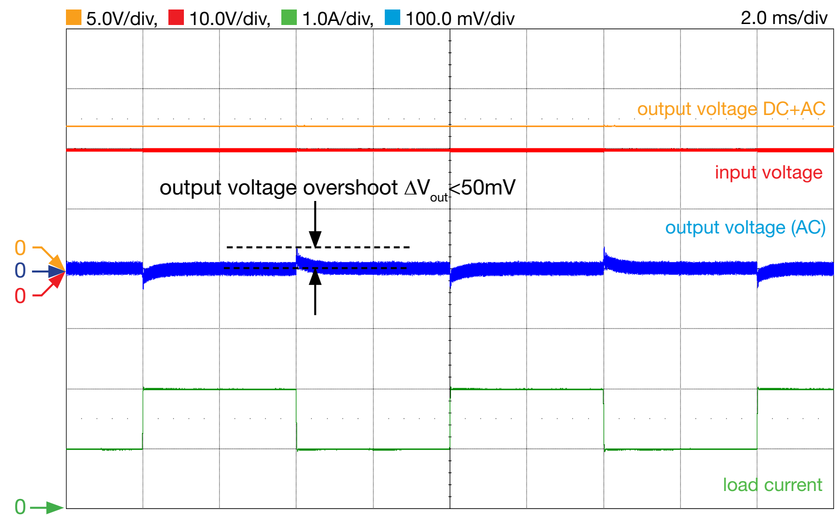


Figure 10. LM5118 Buck-Boost regulator load transient response in BM, with R_{18}, C_{22}, C_{25} connected (higher cross-over frequency): V_{in}=20V, I_{out}=1.0A to 2.0A, f_s=300kHz, L=10µH

The plots of Figures 9 and 10 highlight the influence of the voltage feedback error amplifier setup on the load transient response of the Buck-Boost regulator in Buck Mode. In Figure 9 you see that the magnitude of output voltage surge during the load trasients exceeds 50mV, with lower cross-over error amplifier setup. In Figure 10, instead, you see that the magnitude of output voltage surge during the load trasients is lower than 50mV, with higher cross-over error amplifier setup. Comparing the plots of Figures 9 and 10 respect to Figures 8 and 9 you see that the load transient response in Buck Mode is better than in Buck-Boost Mode. This is the consequence of the higher crossover frequency achieved in Buck Mode with respect to the Buck-Boost Mode, by using the same compensation. Indeed, all the feedback compensations in the TI-PMLK LM5118 Buck boost board have been designed for Buck-Boost Mode. In fact, the Buck-Boost mode represents the worst-case for compensation design, because the Buck-Boost mode introduces a RHP zero in the uncompensated loop gain, which causes a phase lag and requires extra phase boost in the feedback voltage compensation.

Experimental plots

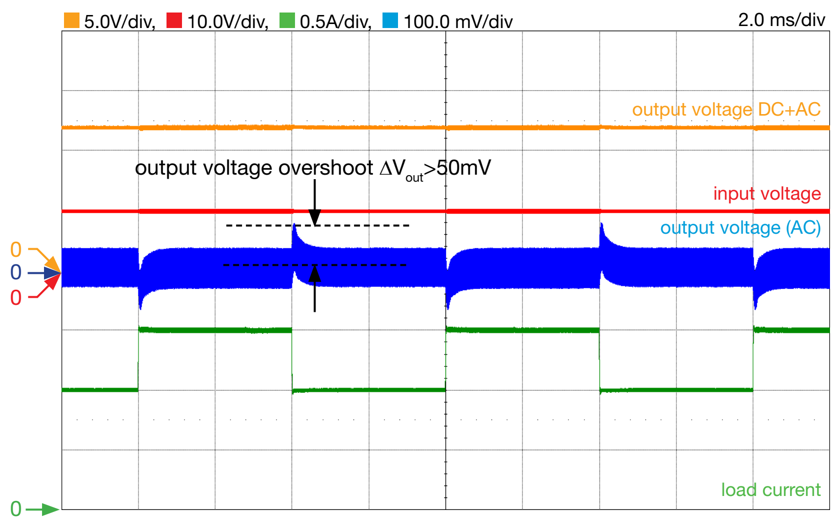


Figure 11. LM5118 Buck-Boost regulator load transient response in BBM, with R_{16}, C_{20}, C_{23} connected (low cross-over frequency): V_{in}=10V, I_{out}=1.0A to 1.5A, f_s=300kHz, L=10µH

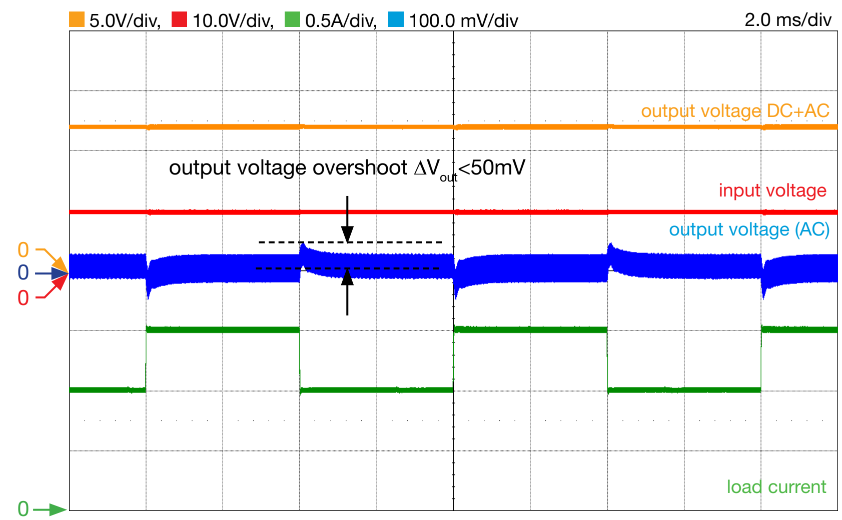


Figure 12. LM5118 Buck-Boost regulator load transient response in BBM, with R_{17}, C_{21}, C_{24} connected (low cross-over frequency): V_{in}=10V, I_{out}=1.0A to 1.5A, f_s=300kHz, L=3.3µH

The plots of Figures 11 and 12 highlight the influence of the inductance and voltage feedback error amplifier setup and on the load transient response of the Buck-Boost regulator in Buck-Boost Mode. In Figure 11 you see that the magnitude of output voltage surge during the load trasients exceeds 50mV, with L=10µH and nominal low crossover error amplifier setup (the R_{16}, C_{20}, C_{23} compensator is designed to achieve 2kHz crossover at V_{in}=6V and I_{out}=3A with L=10µH). In Figure 12, instead, you see that the magnitude of output voltage surge during the load transients is lower than 50mV, with L=3.3µH and nominal low cross-over error amplifier setup (the R_{17}, C_{21}, C_{24} compensator is designed to achieve 1kHz crossover at V_{in}=6V and I_{out}=3A with L=3.3µH). The improvement can be justified by a higher effective crossover frequeny with L=3.3µH compared to L=10µH when the converter operates at V_{in}=10V and I_{out}=1.0A-1.5A. Indeed, the formulae provided in the *Theory Background* section show that the input voltage and the load current influence the magnitude of the DC loop gain T_{u0} and the frequency of the LFP pole ω_{LFP}, thus impacting the crossover frequency for a given error amplifier compensation.

[NOTE: The loop gain crossover can also be influenced by the effect of the inductance on the current loop gain (*see [1]-[4] and the Experiment 3 in TI-PMLK Boost Experiment Book [12] to learn more about the impact of the inductance in current mode controlled dc-dc converters*)]

Experimental plots

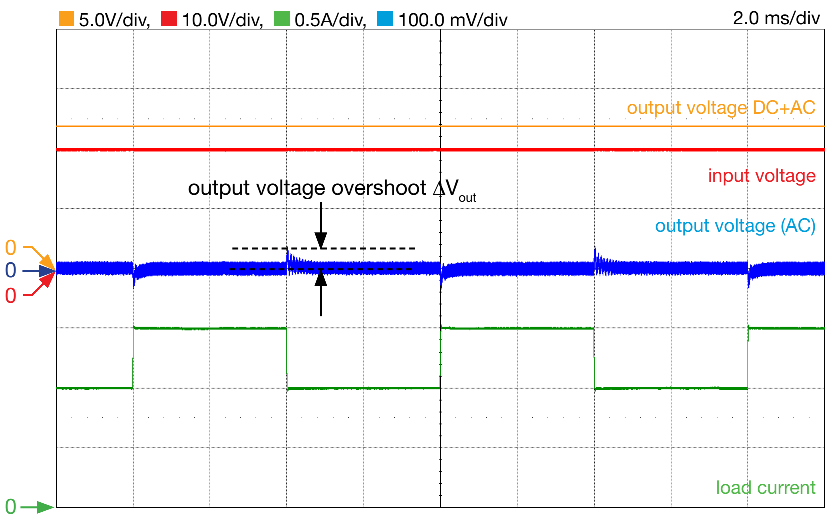


Figure 13. LM5118 Buck-Boost regulator load transient response in BM, with R_{16}, C_{20}, C_{23} connected (low cross-over frequency): V_{in}=20V, I_{out}=1.0A to 1.5A, f_s=300kHz, L=10µH

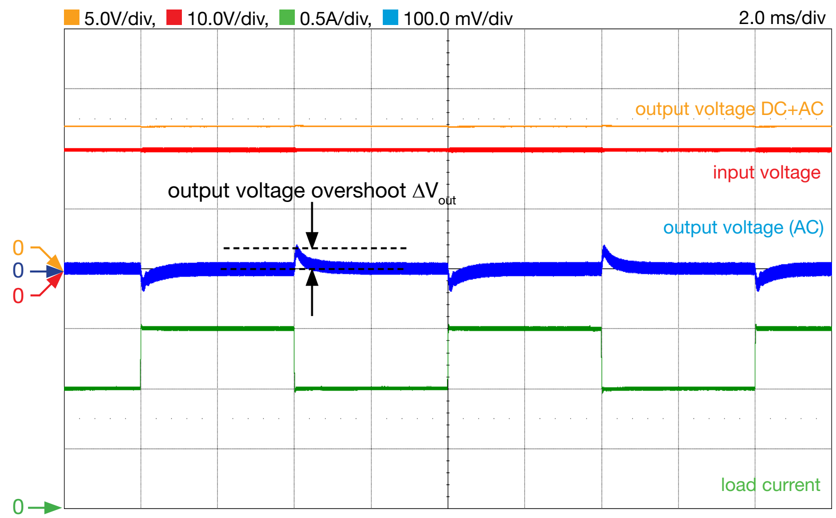


Figure 14. LM5118 Buck-Boost regulator load transient response in BM, with R_{17}, C_{21}, C_{24} connected (low cross-over frequency): V_{in}=20V, I_{out}=1.0A to 1.5A, f_s=300kHz, L=3.3µH

The plots of Figures 13 and 14 compare the load transient response of the Buck-Boost regulator in Buck Mode with two different setup of the inductance and of voltage feedback error amplifier. You can see that the load transient response is characterized by comparable surges magnitude with L=10µH and with L=3.3µH. As discussed in the *Theory Background* section, the simplified dynamic model of Buck-Boost regulator with emulated peak current mode control shows that inductance has not a direct effect on the loop gain in the Buck-Boost converter operating in Buck Mode. However, the dynamic performance can be influenced by the effect of the inductance on the current loop gain (*see [1]-[4] and the Experiment 3 in TI-PMLK Boost Experiment Book [12] to learn more about the impact of the inductance in current mode controlled dc-dc converters*). The compensation adopted for the load transient test with L=3.3µH has been designed to achieve 1kHz crossover at V_{in}=6V and I_{out}=3A in Buck-Boost Mode, whereas the compensation adopted for the load transient test with L=10µH has been designed to achieve 2kHz crossover at V_{in}=6V and I_{out}=3A in Buck-Boost Mode. The operating conditions V_{in}=20V and I_{out}=1.0A-1.5A with the two inductors lead to comparable effective crossover frequency.

Experiment 4

The goal of this experiment is to analyze the influence of the input voltage, load current and feedback compensation setup on the voltage reference tracking capability of the Buck-Boost regulator.

Case Study

The goal of this experiment is to analyze the influence of the voltage feedback loop gain on the soft start performance of a Buck-Boost boost regulator.

The TI-PMLK LM5118 Buck-Boost regulator operates with V_{in}=[6,36] V[(1)], while regulating the output voltage at the nominal value V_{out}=12V in the load current range I_{out}=[0,3]A. Fig.1 shows the simplified circuit schematic of the regulator, including the main external power and control components and the internal architecture of the LM5118 IC. The voltage feedback compensation of the regulator ensures that the output voltage is proportional to the reference voltage V_{ref}. When the regulator is in operation, the value of the reference voltage is 1.23V, which is determined by an internal voltage generator. However, when the regulator is turned ON, the reference voltage rises softly from zero to 1.23V, in order to realize the *soft-start* of the regulator. This is an important feature of all voltage regulators, that allows to reduce the inrush current, the ringing, the stresses, and to prevent malfunctioning during the regulator start up. The so ft start feature is realized by means of the capacitor C_{SS}, which is fed by the IC's internal soft-start ramp generator, thus providing a ramp up of the controller reference voltage V_{ref} from zero to 1.23V at start-up. The value of the capacitance C_{SS} determines the *soft-start time* T_{ss}, which must be sufficiently long to limit the start-up inrush current and to prevent output voltage surges and current limit action. The crossover frequency of the feedback voltage loop gain influences the ability of the regulator to track the V_{ref} ramp-up.

[(1)] Restricted range adopted for this educational board, compared to the 3V to 75V full range of LM5118 [5]

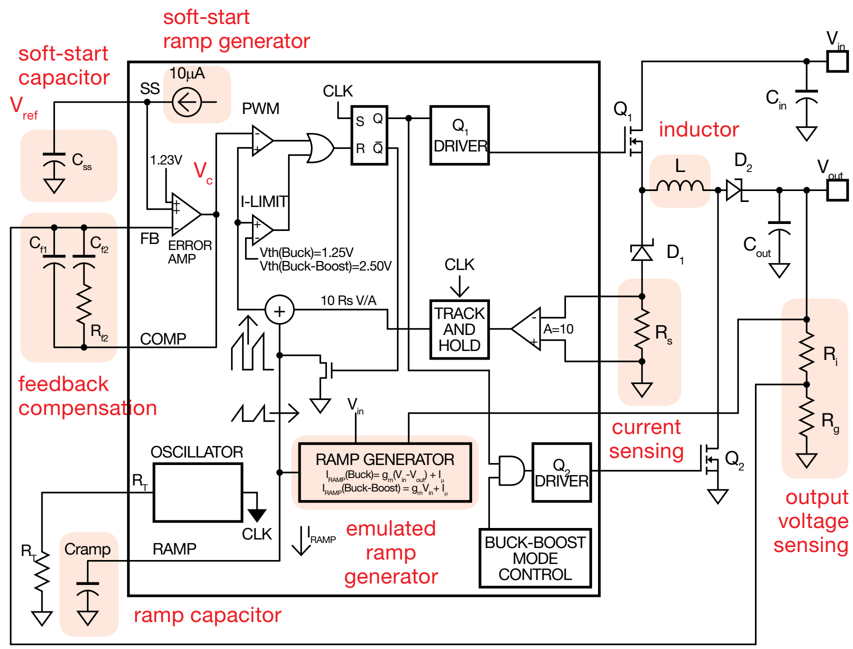


Figure 1. Simplified schematic of the LM5118 Buck boost regulator

Test#1. We observe the start up of the LM5118 Buck boost regulator with different input voltage values, feedback compensation and soft start time. We analyze the output voltage, inductor current and soft start capacitor voltage and investigate the regulator reference voltage tracking capability. The different start-up responses observed for the LM5118 Buck boost regulator in Buck Mode and Buck-Boost Mode operation are discussed.

Test#2. We observe the start up of the LM5118 Buck boost regulator with different input voltage values, load current, inductance and relevant feedback compensation. We analyze the output voltage, inductor current and soft start capacitor voltage and investigate the regulator reference voltage tracking capability.

Theory Background

The simplified low frequency ac model for the analysis of the output voltage and inductor current of Buck-Boost regulator at the start-up are provided below. (*see [1]-[4] for more details on Buck-Boost dynamic modeling and control design and [5] for more details on LM5118 operation and features*)

Figure 2 shows a simplified circuit schematic of LM5118 Buck-Boost regulator, with emphasis on feedback compensation and on the variables V_{ref}, i_L and V_{out} of interest during the start-up.

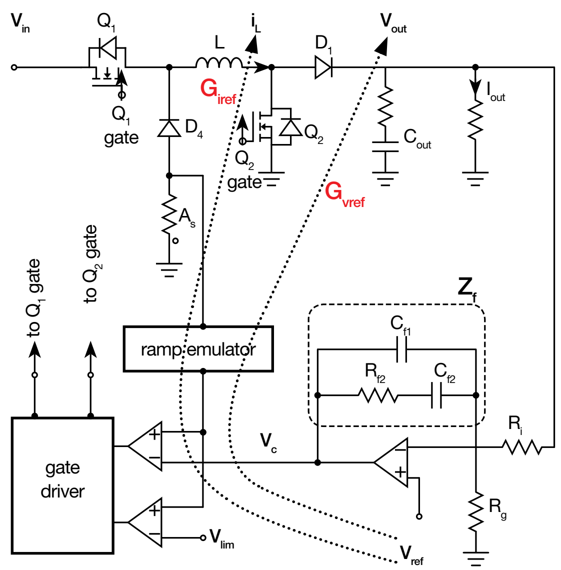


Figure 2

The voltage feedback loop gain depends on the operation mode of the LM5118 Buck boost regulator (see *Experiment 3* for more details). The feedback compensation impedance Z_f is normally designed starting from the desired crossover frequency f_c and phase margin φ_c to be achieved with the compensated loop gain. The crossover frequency is set much lower than the switching frequency f_s. Typically, it is $f_c < f_s/10$ ([1]-[3]). In current mode controlled dc-dc regulators, Type II compensators are mostly used. The gain of a Type II compensator is given in (1):

(1) $$G_c(s) \cong \frac{\omega_0}{s}\left[1+\frac{s}{\omega_Z}\right]\left[1+\frac{s}{\omega_P}\right]^{-1}$$

Formulae for the Type II compensator design are (*see [1]-[3]*):

(2) $$C_{f1}=\frac{|T_u(\omega_c)|}{2\pi f_c R_i K};\; C_{f2}=(K^2-1)C_{f1};\; R_{f2}=\frac{K}{2\pi f_c C_{f2}}$$

(3) $$K=\tan\left[\tfrac{1}{2}\varphi_b+45^\circ\right];\; \varphi_b=\varphi_c-\varphi_u+90^\circ;\; R_i=R_g\frac{(1-H)}{H}$$

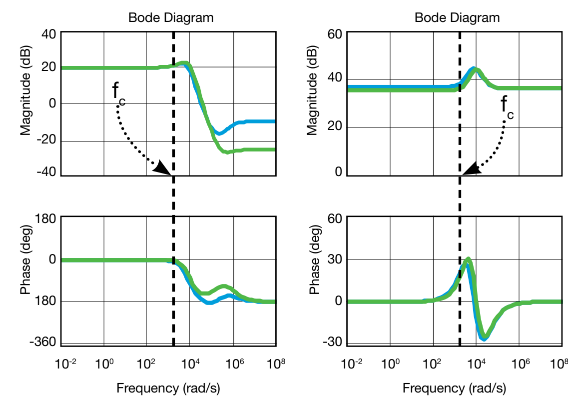
(4) $$\varphi_u=\tan^{-1}\left[\frac{2\pi f_c}{\omega_{ESR}}\right]-\tan^{-1}\left[\frac{2\pi f_c}{\omega_{RHP}}\right]-\tan^{-1}\left[\frac{2\pi f_c}{\omega_{LFP}}\right]$$

In closed loop operation, at low frequency, the emulated current control makes the inductor current almost proportional to the control signal v_c generated by the error amplifier: $\hat{i}_L \cong \hat{v}_c / A_s$. Then, the ac output voltage and the ac inductor current depend on the reference voltage through the gain functions (5) and (6):

(5) $$G_{vref}=\frac{\hat{v}_{out}}{\hat{v}_{ref}}=\frac{T_u}{H}\frac{H+G_c}{1+G_cT_u}\underset{\omega\to 0}{\rightarrow}\frac{1}{H}$$

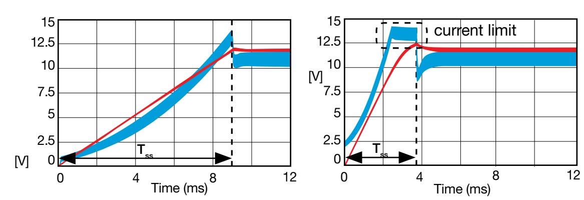
(6) $$G_{iref}=\frac{\hat{i}_L}{\hat{v}_{ref}}=\frac{1}{A_sH}\frac{H+G_c}{1+G_cT_u}\underset{\omega\to 0}{\rightarrow}\frac{1}{A_sT_uH}$$

where $H=R_g/(R_i+R_g)=V_{ref}/V_{out}$, and A_s is the current sensing gain. Figure 3 shows the Bode plots of G_{vref} and G_{iref} gains, resulting from 4kHz crossover design in Buck-Boost Mode at V_{in}=6V and I_{out}=3A. The plots show that the crossover frequency represents the bandwidth of the G_{vref} and G_{iref} gains with repect to the reference voltage. Thus, a higher cross over frequency results in better reference voltage tracking capability of the regulator. If the reference voltage increases too fast during the start-up, a high crossover compensation forces the inductor current to over shoot to deliver the power needed to rapidly charge the output capacitor. Then, the control voltage V_c generated by the compensator can reach the current limit threshold $V_{lim}=A_sI_{Lpk,lim}$, where $I_{Lpk,lim}$ is the programmed current limit peak for the inductor current. Therefore, the fast reference tracking capability expected as a result of the compensator setup for high crossover, can be not realistically achievable due to current limit action when the soft start time T_{ss} is too short or the current limit is too low. Figure 4 shows two different start-up conditions, with and without current limit action.



(a) G_{vref} (b) G_{ivref}

Figure 3: —— V_{in}=6V@I_{out}=3A; —— V_{in}=12V@I_{out}=1A



(a) T_{ss} =9ms (b) T_{ss} =3ms

Figure 4: start-up with V_{in} = 6V@I_{out} = 3A; —— i_L; —— V_{out};
(a) no current limit action; (b) current limit action

Experiment set-up: configuration

The instruments needed for this experiment are: a DC POWER SUPPLY, an OSCILLOSCOPE, a WAVEFORM GENERATOR, three 50W power resistors with 10Ω, 15Ω and 22Ω resistance. Figure 4 shows the instruments connections. Follow the instructions provided in next page to set-up the connections.

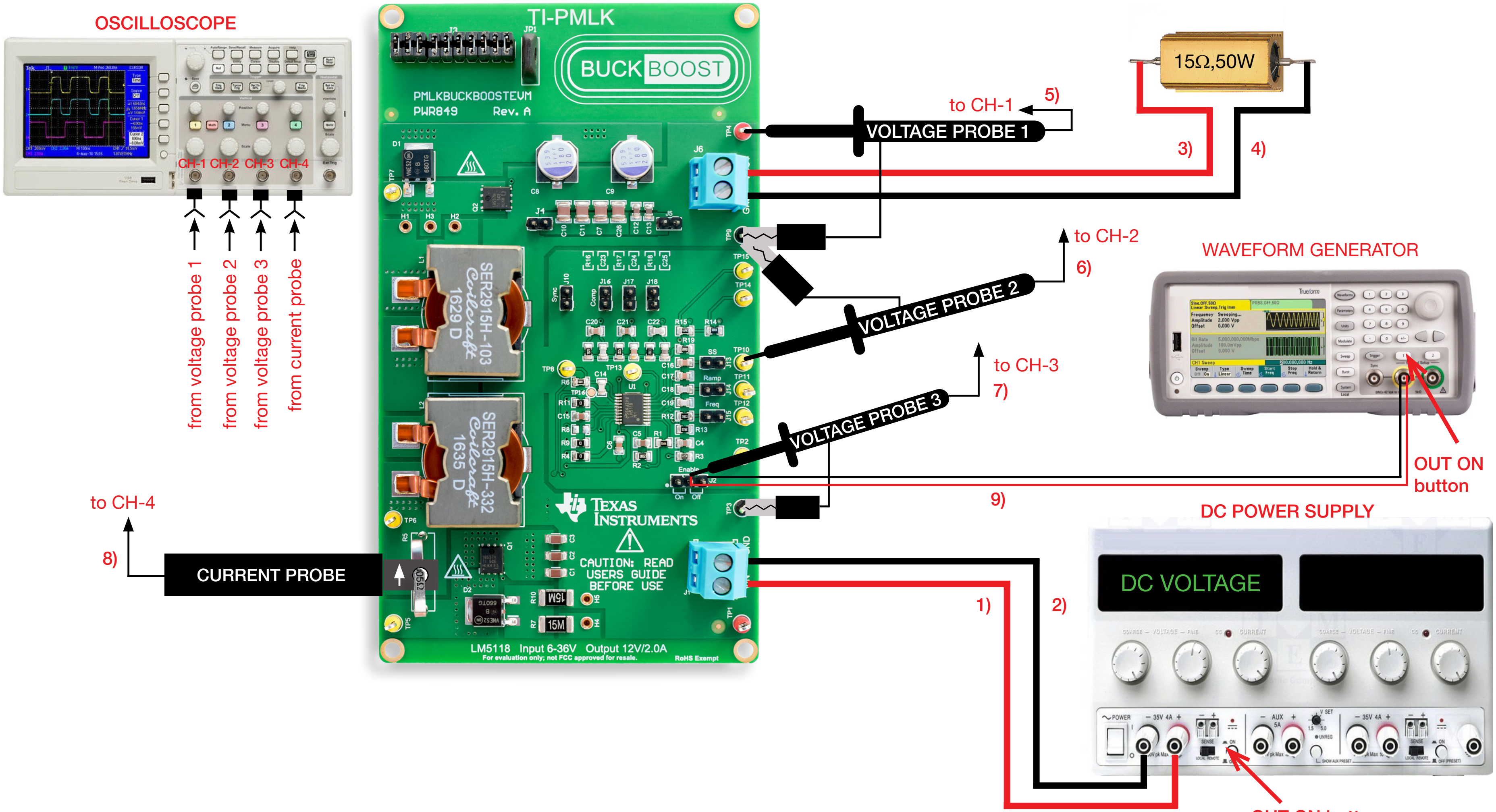


Figure 5. Experiment set-up.

Experiment set-up: instructions

With all the instruments turned off, make the following **connections**:

1) connect the POSITIVE (RED) OUTPUT of the DC POWER SUPPLY to the INPUT (VIN) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

2) connect the NEGATIVE (BLACK) OUTPUT of the DC POWER SUPPLY to the GROUND (GND) of the J_1 screw terminal of the LM5118 Buck-Boost regulator

3) connect the OUTPUT (VOUT) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to one terminal of a 15Ω/50W power resistor
   [**NOTE:** A passive resistive load is needed for the start-up test. Simple passive power resistors can be used, as in this example. A 15Ω passive resistor is used in Test#1, whereas a 10Ω and a 22Ω resistors are used in Test#2. An electronic load in adjustable constant resistance mode is a possible alternative.]

4) connect the GROUND (GND) of the J_6 screw terminal of the LM5118 Buck-Boost regulator to the other terminal of the15Ω/50W power resistor

5) connect a voltage probe to channel 1 of the oscilloscope and hang it on the TEST PIN TP_4 which is the output voltage of the LM5118 Buck-Boost regulator

6) connect a voltage probe to channel 2 of the oscilloscope and hang it on the TEST PIN TP_{10} which is the soft-start capacitor voltage of the LM5118 Buck-Boost regulator

7) connect a voltage probe to channel 3 of the oscilloscope and hang it on the center PIN of the jumper J_2 which is the enable voltage of the LM5118 Buck-Boost regulator

8) connect a current probe to channel 4 of the oscilloscope and hang it on the sensing resistor R_5 of the LM5118 Buck-Boost regulator, ensuring that the arrow printed on the probe clamps corresponds to the current that enters the inductor (the arrow must point upside when looking the LM5118 Buck-Boost board frontally, as shown in Figure 5)

9) connect the positive pole of the WAVEFORM GENERATOR output to the center PIN of the jumper J_2, which is the enable voltage of the LM5118 Buck-Boost regulator, and the negative pole to the ground pin of the jumper J_2.

Test#1: preparation and procedure

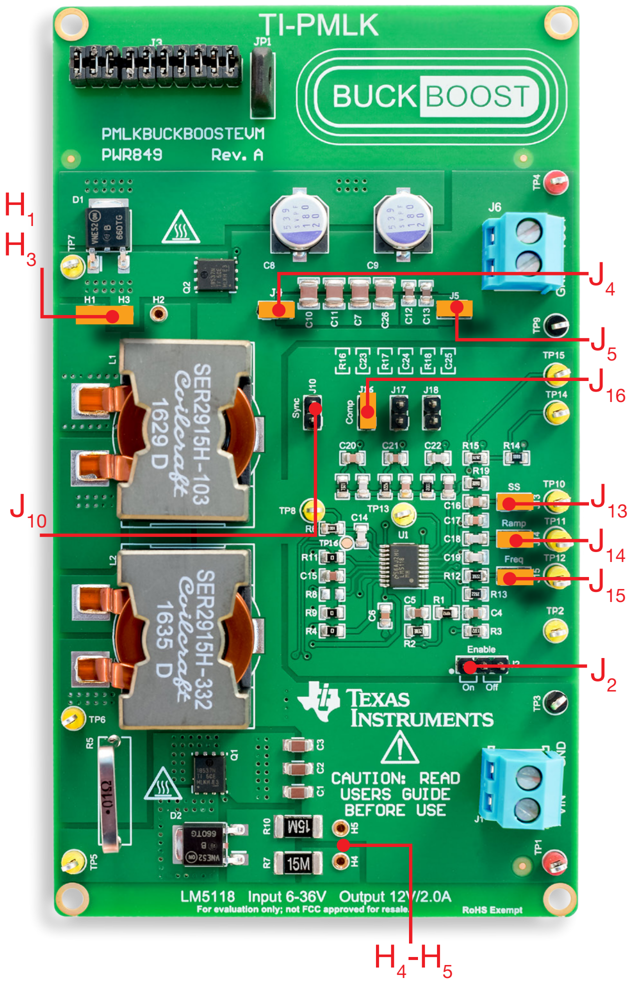


Figure 6. LM5118 board: jumpers set-up for Test#2

Initial jumpers set-up (see Figure 6):

- J_2 **open**
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22μF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47μF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **shorted** → 33nF+68nF soft start caps connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10μH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10μH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) turn on the OSCILLOSCOPE, set CH-1, CH-2 and CH-3 in DC 1MΩ coupling mode, set CH-4 in DC 50Ω coupling mode, execute the “de-gauss” of the current probe to remove possible dc bias in the current probe, select CH-3 as trigger source, with triggering on positive slope at 2V level, set the time base at 1MS/s sampling rate with 5ms/div scope resolution, set the bandwidth of all channels lower than 100MHz, and adopt a +2bit digital filtering (if allowed by the oscilloscope)
2) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 7A
3) turn on the WAVEFORM GENERATOR (ensure that the “OUT ON” button is OFF), set the OUT in square wave mode, with 0.1Hz frequency, 2% duty-cycle, $4.0V_{pp}$ amplitude, 2.0V offset, high impedance output mode
4) turn ON the POWER SUPPLY “OUT ON” button and then the WAVEFORM GENERATOR "OUT ON" button. In these conditions, you should see the output voltage on the CH-1 trace to rise straight from zero to 12V and then to settle at 12V (with possible overshoot), the soft start capacitor voltage on the CH-2 trace to rise straight from zero to 1.23V and then to settle at 1.23V, the waveform generator output voltage on CH-3 trace as a step-wise line from zero to 4V, and the inductor current on the CH-4 trace of the OSCILLOSCOPE as waveform to rise from zero to 1.5A and to settle at 1.5A (with possible overshoot). (If the waveforms do not look as described above, turn OFF the “OUT ON” button of the DC POWER SUPPLY and verify the previous steps)
5) measure the magnitude of the overshoots of the output voltage (if any) and of the inductor current and the duration of the soft-start time and record the values in Table 1
6) repeat the step 5) for the input voltage values listed in Table 1 (you do not need to turn OFF the POWER SUPPLY “OUT ON” button while adjusting the input voltage)
7) turn OFF the “OUT ON” button of the WAVEFORM GENERATOR and the “OUT ON” button of the DC POWER SUPPLY, then open the J_{16} jumper to disconnect the R_{16}, C_{20}, C_{23} parts to the error amplifier and short the jumper J_{18} to connect the R_{18}, C_{22}, C_{25} parts to the error amplifier, repeat the steps 4) to 7), and report the results in Table 1
8) turn OFF the “OUT ON” button of the WAVEFORM GENERATOR and the “OUT ON” button of the DC POWER SUPPLY, then open the J_{14} jumper to reduce the soft-start capacitance to 68nF, repeat the steps 4) to 7), and report the results in Table 1
9) at the end of the measurements, turn OFF the “OUT ON” button of the WAVEFORM GENERATOR and the “OUT ON” button of the DC POWER SUPPLY, then switch off all the instruments

Test#1: measure and calculate

For the operating conditions of Table 1, following the instructions provided in the preceding *Preparation and Procedure* section, measure the magnitude of the output voltage overshoot with respect to 12V and of the inductor current overshoot with respect to the DC value reached by the current after the start up, measure the soft start time, and report the results in Table 1, and answer the questions.

Table 1. Output voltage and inductor current overshoots during the soft start of LM5118 Buck boost regulator at f_s = 300kHz with L = 10µH for different input voltage and compensation setup.

(1) ΔV_{out} [mV]	(2) ΔI_L [mV]	(3) T_{ss} [ms]	case (a): J_{16} sh, J_{17} op, J_{18} op			case (b): J_{16} op, J_{17} op, J_{18} sh		
C_{ss} = 110nF [J_{13} shorted]		V_{in}=10V	(1)	(2)	(3)	(1)	(2)	(3)
		V_{in}=20V	(1)	(2)	(3)	(1)	(2)	(3)
C_{ss} = 68nF [J_{13} open]		V_{in}=10V	(1)	(2)	(3)	(1)	(2)	(3)
		V_{in}=20V	(1)	(2)	(3)	(1)	(2)	(3)

feedback error amplifier compensation				current sensing resistance		emulated ramp capacitor		output voltage divider high-side resistance
	C_{f1}	C_{f2}	R_{f2}	R_s [mΩ]		C_{ramp} [pF]		R_i=2.67kΩ
J_{16} sh [H_1-H_3 sh]	3.3nF	33nF	7.32kΩ	H_4-H_5 op	15	J_{14} op	150	output voltage divider low-side resistance
J_{17} sh [H_2-H_3] sh	10nF	100nF	4.22kΩ	H_4-H_5 sh	7.5	J_{14} sh	330	R_g=309Ω
J_{18} sh [H_1-H_3] sh	470pF	22nF	13.3kΩ	inductance		switching frequency		current sensing gain
output capacitor				L [µH]		f_s [kHz]		A_s=10R_s
J_4 op, J_5 op	C_{out} = 2x180µF, 25mΩ(el)			H_1-H_3 sh	10	J_{15} op	150	ramp transconductance and bias
J_4 sh, J_5 sh	C_{out} = 2x180µF, 25mΩ(el)//4x22µF(cer)//2x0.47µF(cer)			H_2-H_3 sh	3.3	J_{15} sh	300	g_m=5µA/V, I_μ=50µA

Answer:

1. Is there any output voltage overshoot during the soft-start? ☐ yes ☐ no ☐ it depends on feedback compensation ☐ it depends on input voltage
2. Is there any inductor current overshoot during the soft-start? ☐ yes ☐ no ☐ it depends on feedback compensation ☐ it depends on input voltage
3. Is the output voltage waveform similar to the soft start capacitor voltage ? ☐ yes ☐ no ☐ it depends on feedback compensation ☐ it depends on input voltage

Test#2: preparation and procedure

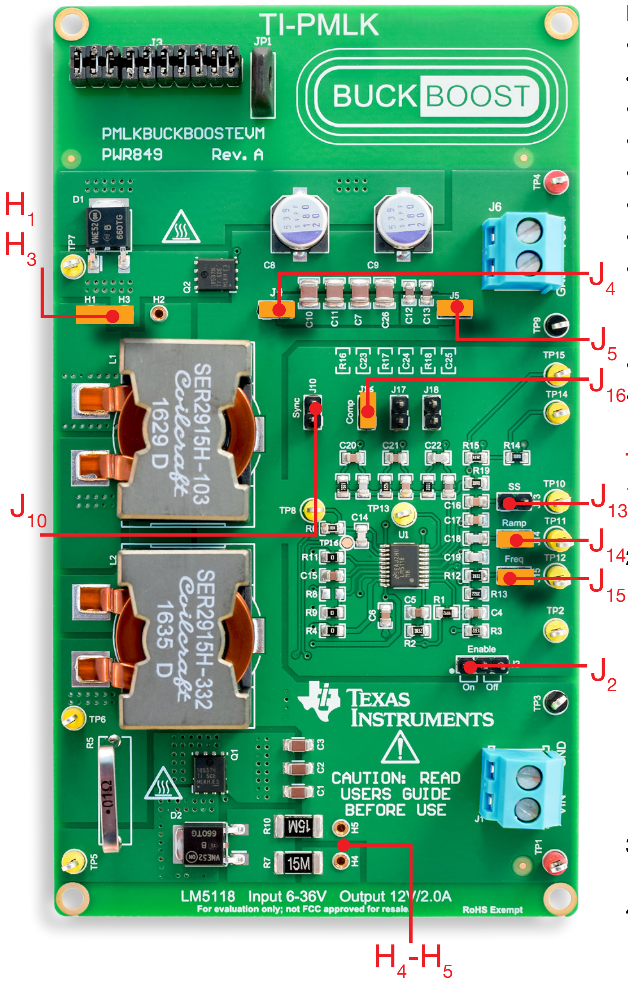


Figure 7. LM5118 board: jumpers set-up for Test#2

Initial jumpers set-up (see Figure 6):

- J_2 **open**
- J_4 **shorted** → C_7, C_{10}, C_{11}, C_{26} (4x22μF) output caps connected
- J_5 **shorted** → C_{12}, C_{13} (2x0.47μF) output caps connected
- J_{10} **open** → internal synchronization
- J_{13} **open** → 68nF soft start capacitor connected
- J_{14} **shorted** → 330pF ramp capacitor connected
- J_{15} **shorted** → switching frequency f_s = 300kHz
- J_{16} **shorted**, J_{17} **open**, J_{18} **open** → error amplifier setup with parts R_{16}, C_{20}, C_{23} connected (low cross-over frequency with $L = L_3$ =10μH, and high slope compensation ramp)
- H_1-H_3 **shorted** → L_1 (10μH) inductor connected
- H_4-H_5 **open** → R_{sns}=15mΩ sensing resistance setup

Test Procedure:

1) connect the 10Ω/50W power resistor to the output of the LM5118 Buck boost regulator
2) turn on the OSCILLOSCOPE, set CH-1, CH-2 and CH-3 in DC 1MΩ coupling mode, set CH-4 in DC 50Ω coupling mode, execute the "de-gauss" of the current probe to remove possible dc bias in the current probe, select CH-3 as trigger source, with triggering on positive slope at 2V level, set the time base at 1MS/s sampling rate with 5ms/div scope resolution, set the bandwidth of all channels lower than 100MHz, and adopt a +2bit digital filtering (if allowed by the osciloscope)
3) turn on the POWER SUPPLY (with OUT ON button OFF), set the voltage at 10V, and set the CURRENT LIMIT > 6A
4) turn on the WAVEFORM GENERATOR (ensure that the "OUT ON" button is OFF), set the OUT in square wave mode, with 0.1Hz frequency, 2% duty-cycle, 4.0V_{pp} amplitude, 2.0V offset, high impedance output mode
5) turn ON the POWER SUPPLY "OUT ON" button and then the WAVEFORM GENERATOR "OUT ON" button. In these conditions you should see the output voltage on the CH-1 trace to rise straight from zero to 12V and then to settle at 12V (with possible overshoot), the soft start capacitor voltage on the CH-2 trace to rise straight from zero to 1.23V and then to settle at 1.23V, the waveform generator output voltage on CH-3 trace as a step-wise line from 0 to 4V, and the inductor current on the CH-4 trace of the OSCILLOSCOPE as waveform rising from 0 to 1.5A and then to settle at 1.5A (with possible overshoot), (if the waveforms do not look as described above, turn OFF the "OUT ON" button of the DC POWER SUPPLY and verify the previous steps)
6) measure the magnitude of the overshoots of the output voltage (if any) and of the inductor current and the duration of the soft-start time and record the values in Table 2
7) repeat the step 5) for the input voltage values listed in Table 2 (you do not need to turn OFF the POWER SUPPLY "OUT ON" button while adjusting the input voltage);
8) turn OFF the "LOAD ON" button of the ELECTRONIC LOAD and the "OUT ON" button of the DC POWER SUPPLY, then open the H_1-H_3 jumper to disconnect the 10μH inductor, short the H_2-H_3 jumper to connect the 3.3μH inductor, open the J_{16} jumper to disconnect the R_{16}, C_{20}, C_{23} parts from the error amplifier and short the jumper J_{17} to connect the R_{17}, C_{21}, C_{24} parts to the error amplifier, repeat the steps 4) to 7), and report the results in Table 2
9) turn OFF the "OUT ON" button of the WAVEFORM GENERATOR and the "OUT ON" button of the DC POWER SUPPLY, then disconnect the 10Ω/50W power resistor from the output of the LM5118 Buck boost regulator, connect the 22Ω/50W power resistor, repeat the steps 5) to 8), and report the results in Table 2
10) at the end of the measurements, turn OFF the "OUT ON" button of the WAVEFORM GENERATOR and the "OUT ON" button of the DC POWER SUPPLY, then switch off all the instruments

Experiment 4

Test#2: measure and calculate

For the operating conditions of Table 2, following the instructions provided in the preceding *Preparation and Procedure* section, measure the magnitude of the output voltage overshoot with respect to 12V and of the inductor current overshoot with respecd to the DC value reached by the current after the start up, measure the soft start time, and report the results in Table 2, and answer the questions.

Table 2. Output voltage and inductor current overshoots during the soft start of LM5118 Buck boost regulator at f_s = 300kHz, for different inductors and compensation setup.

(1) ΔV_{out} [mV]	(2) ΔI_L [mV]	(3) T_{ss} [ms]	case (a): L=10µH H_1-H_3 sh, J_{16} sh, J_{17} op, J_{18} op			case (b): L=3.3µH H_2-H_3 sh, J_{16} op, J_{17} sh, J_{18} op		
R_{load} = 10Ω		V_{in}=10V	(1)	(2)	(3)	(1)	(2)	(3)
		V_{in}=20V	(1)	(2)	(3)	(1)	(2)	(3)
R_{load} = 22Ω		V_{in}=10V	(1)	(2)	(3)	(1)	(2)	(3)
		V_{in}=20V	(1)	(2)	(3)	(1)	(2)	(3)

feedback error amplifier compensation				current sensing resistance		emulated ramp capacitor		output voltage divider high-side resistance
	C_{f1}	C_{f2}	R_{f2}	R_s [mΩ]		C_{ramp} [pF]		R_i=2.67kΩ
J_{16} sh [H_1-H_3 sh]	3.3nF	33nF	7.32kΩ	H_4-H_5 op	15	J_{14} op	150	output voltage divider low-side resistance
J_{17} sh [H_2-H_3] sh	10nF	100nF	4.22kΩ	H_4-H_5 sh	7.5	J_{14} sh	330	R_g=309Ω
J_{18} sh [H_1-H_3] sh	470pF	22nF	13.3kΩ	inductance		switching frequency		current sensing gain
output capacitor				L [µH]		f_s [kHz]		A_s=10R_s
J_4 op, J_5 op	C_{out} = 2x180µF, 25mΩ(el)			H_1-H_3 sh	10	J_{15} op	150	ramp transconductance and bias
J_4 sh, J_5 sh	C_{out} = 2x180µF, 25mΩ(el)//4x22µF(cer)//2x0.47µF(cer)			H_2-H_3 sh	3.3	J_{15} sh	300	g_m=5µA/V, I_μ=50µA

Answer:

1. Is there any output voltage overshoot during the soft-start? ☐ yes ☐ no ☐ it depends on inductor/compensation ☐ it depends on input voltage/load current
2. Is there any inductor current overshoot during the soft-start? ☐ yes ☐ no ☐ it depends on inductor/compensation ☐ it depends on input voltage/load current
3. Is the output voltage waveform similar to the soft start capacitor voltage ? ☐ yes ☐ no ☐ it depends on inductor/compensation ☐ it depends on input voltage/load current

Discussion

In Test#1 we are interested in investigating correlations among the start-up response of the Buck-Boost regulator and the setup of feedback compensation and soft start time.

The reference-to-output voltage gain function G_{vref} and the reference-to-inductor current gain function G_{iref} introduced in the *Theory Background* section help understanding how the soft start rise of the reference voltage has to be coordinated with the loop gain crossover frequency. The G_{vref} and G_{iref} plots of Figure 4 show that if the bandwidth of the signal $v_{ref}(t)$ is lower than one tenth of the loop gain crossover frequency, the output voltage and the inductor current are purely proportional to it. In other words, you will see the output voltage and the inductor current to show the same waveform of the reference voltage signal. During the soft start, the reference voltage $v_{ref}(t)$ follows the soft start capacitor voltage, until it is lower than the V_{BG}=1.23V voltage of the internal board generator. The soft start capacitor voltage rises linearly during the soft start time T_{ss} = 10µA/C_{ss}, where 10µA is the current injected into the C_{ss} soft start capacitance by the internal current generator of the LM5118 (see the architecture of the LM5118 shown in Figure 1). The slope of the soft start capacitor voltage is given by $s_{ref}=V_{BG}/T_{ss}$. If the regulator has to track a ramp reference voltage with such slope, it means that it has to be able to track a sinusoidal voltage whose magnitude equals V_{BG} and whose equivalent frequency is such that the maximum value of its derivative equals the slope value s_{ref}. Based on these assumptions, it can be easily proved that the equivalent frequency $f_{eq,ss}$ of the sinusoid representing the soft start capacitor ramp voltage in the frequency domain is $f_{eq,ss}=1/(2\pi T_{ss})$. The condition $f_{eq,ss} << f_c$ has then to be fulfilled to obtain an output voltage and an inductor current reproducing perfectly the soft start ramp voltage. The soft start times obtained in LM5118 Buck boost regulator with C_{ss}=110nF (jumper J_{14} shorted) and C_{ss}=68nF (jumper J_{14} open) correspond to about 12ms and 8ms, which are equivalent to 13Hz and 20Hz equivalent ac frequencies, respectively. These frequencies are much lower than the crossover frequency of the LM5118 Buck boost regulator in both Buck and Buck-Boost Mode, which is in the range 1kHz-10kHz for operating conditions and feedback compensation setup of Test#1. For this reason, no overshoot is observed in the output voltage in Test#1, and the output voltage is a perfect reproduction of the soft start capacitor voltage. The inductor current, instead, does not look exactly like the soft start capacitor voltage. In particular, in Buck Mode the inductor current shows an overshoot before flattening to the steady state value, which is equal to load current I_{out} in Buck Mode. This is motivated by the ability of the inductor in delivering the instant current needed to the load, $i_{load}(t)=v_{out}(t)/R_{load}$, plus the instant current needed to charge up the output capacitor, $i_{Cout}(t)=C_{out}V_{out,nom}/T_{ss}$, where $V_{out,nom}$=12V. When the output voltage flattens to 12V, no more current is needed to charge the output capacitor, and then the inductor current is promptly regulated to $I_{load}=V_{out,nom}/R_{load}$ (see Figures 7 and 8). So that, the overshoot in the inductor current is not due to a lack of tracking capability of the regulator, but rather it is the effect of its perfect tracking capability. As a proof of this, the increase of the extra current delivered by the inductor can be easily observed in the case the soft start time is reduced from 12ms (Figure 7) to 8ms (Figure 9). In Buck-Boost Mode, the inductor current waveform looks much different than the Buck Mode. In fact, there is an initial interval during which the LM5118 operates in Buck Mode, as the required output voltage is still sufficiently lower than the input voltage. Then, after a short transition time, the LM5118 moves into the Buck-Boost Mode. This motivates the apparently strange waveform of the inductor current during the start-up. You can observe that, when the LM5118 regulator moves from Buck Mode into Buck-Boost Mode, the extra inductor current required to charge the output capacitor increases. The increase factor is about $1/(1-D_{BBM})$, where D_{BBM} is the duty-cycle in Buck-Boost Mode (see the *Experiment 1* for details on how to calculate the duty-cycle in Buck-Boost Mode), as in Buck-Boost Mode the inducrtor current is delivered to the output only during the ON time of diode D2, which is the $(1-D_{BBM})$ fraction of the switching period.

In Test#2 we are interested in investigating correlations among the start-up response of the Buck-Boost regulator, the inductance and the feedback compensation.

The Test#2 is realized with two different inductances L_1 = 10µH and L_2 = 3.3µH and relevant feedback compensation setup, under two sets of input voltage and load current. The results of the Test#2 confirm the results from Test#1 as discussed above on the reference tracking capability, as the selected feedback compensation ensures that the equivalent ac frequency of the soft start capacitor voltage ramp slope is much lower than the crossover frequency, even with the 3.3µH inductor. The load current impacts simply the final DC level and the slope of the inductor current during the start-up.

Experimental plots

The plots collected in the Figures 7 to 18 show some examples of the soft start in the LM5118 Buck-Boost regulator.

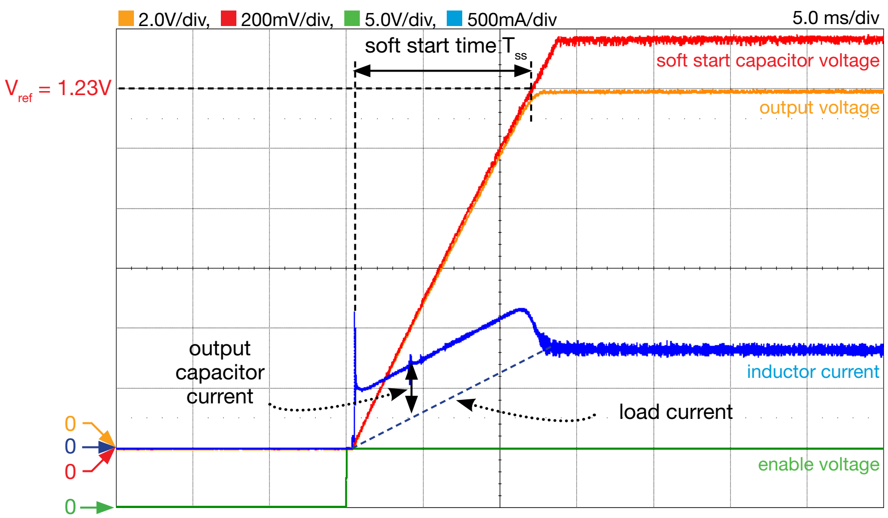


Figure 7. LM5118 Buck-Boost regulator soft start in BM, with R_{18} C_{22}, C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10μH, C_{ss}=110nF.

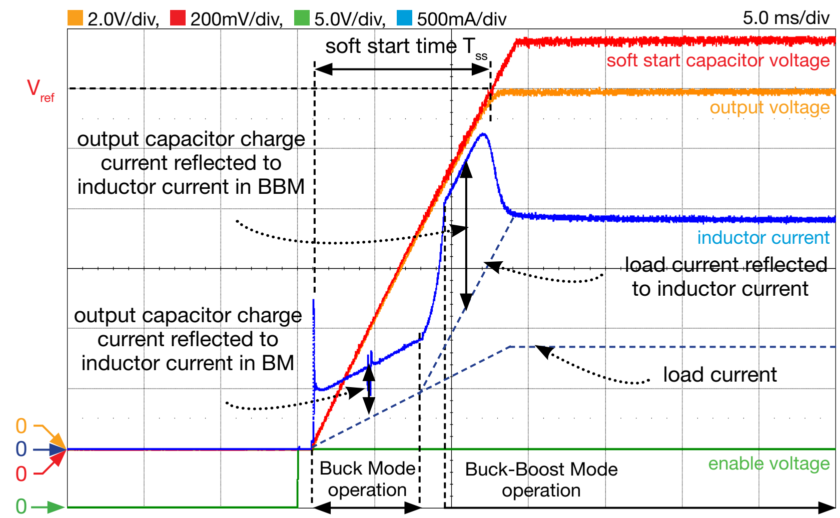


Figure 8. LM5118 Buck-Boost regulator soft start in BBM, with R_{18} C_{22}, C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10μH, C_{ss}=110nF.

The plots of Figures 7 and 8 highlight the difference between the soft-start of the LM5118 Buck boost regulator in Buck Mode (Figure 7) and in Buck-Boost Mode (Figure 7). In Figure 7 you see that the output voltage ramps up with constant slope, emulating perfectly the soft start capacitor voltage ramp. The soft start time T_{ss} with C_{ss}=110nF is about 12ms. The start-up ends when the stoft-start caacitor voltage equals the 1.23V internal reference voltage of the LM5118. The crossover frequency of the regulator in the test conditions of Figure 7 is about 1kHz. The soft start time T_{ss}=12ms, which correspond to an equivalent sinusoidal frequency $f_{eq}=1/(2\pi T_{ss})$=13.3Hz, is much lower than the crossover frequency. This is coherent with the perfect reference voltage tracking capability of the regulator, which prevents output voltage overshoots during the start-up. The inductor current shows an overshoot, instead, before flattening to the steady state value (equal to load current I_{out}=0.8A). As illustrated in the *Discussion* section, this is motivated by the ability of the inductor in delivering the instant current needed to the load, $i_{load}(t)=v_{out}(t)/R_{load}$, plus the instant current needed to charge up the output capacitor, $i_{Cout}(t)=C_{out}V_{out,nom}/T_{ss}$, where $V_{out,nom}$=12V. The plots of Figure 8 show that in Buck-Boost Mode the initial LM5118 operates in Buck Mode, followed by a transition interval, and then by the Buck-Boost Mode operation. The plot highlights in particular that that the inductor current tracks the load current plus the output capacitor current in Buck Mode, whereas it tracks a ramp of higher slope in Buck-Boost Mode, as in Buck-Boost Mode the inductor current is delivered to the output only during one portion of the switching period, as illustrated in the *Discussion* section.

[NOTE: the acquisitions shown in Figures 7 to 18 have been realized with a digital oscilloscope, by setting the sampling rate at 2.5MS/s and applying a +2bits digital filtering to the waveforms, in order to mask the ripple at the switching frequency. This procedure allows to better visualize the average value of the output voltage and of the inductor current during the start-up]

Experimental plots

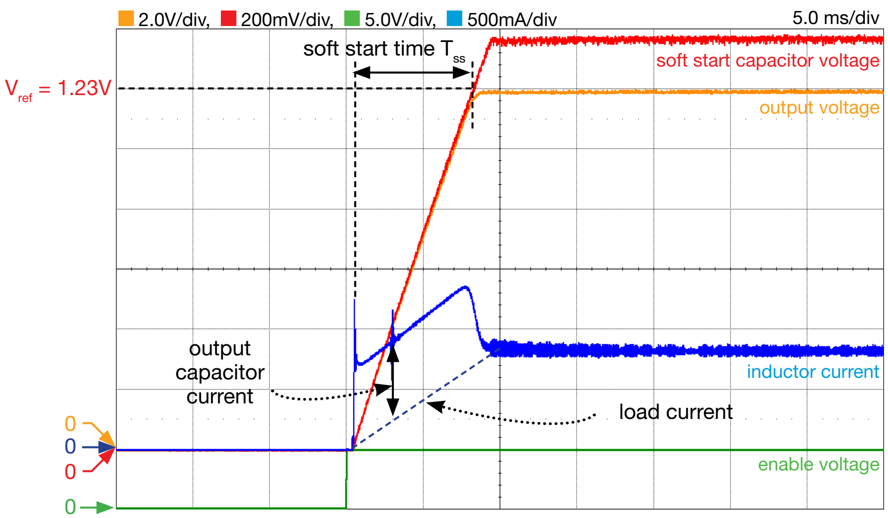


Figure 9. LM5118 Buck-Boost regulator soft start in BM, with R_{16} C_{20}, C_{23} connected (low cross-over frequency): V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10µH, C_{ss}=68nF.

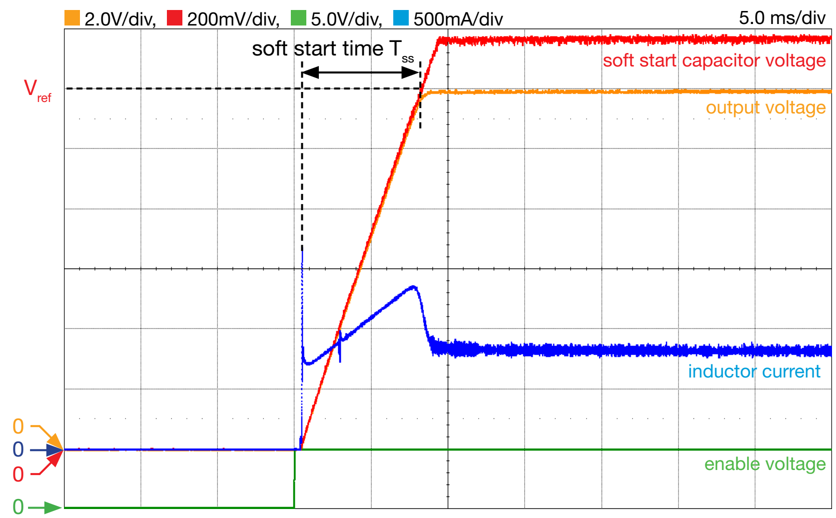


Figure 10. LM5118 Buck-Boost regulator soft start in BBM, with R_{18} C_{22}, C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10µH, C_{ss}=68nF.

The plots of Figures 9 and 10 show the soft-start of the LM5118 Buck boost regulator in Buck Mode with a soft start time of about 8ms, obtained by reducing the soft start capacitance to 68nF. You see that the output voltage emulates perfectly the soft start capacitor voltage ramp, with feedback compensation setup for lower crossover (Figure 9) and higher crossover (Figure 10). Indeed, the soft start time T_{ss} with C_{ss}=68nF is about 8ms, which correspond to an equivalent sinusoidal frequency $f_{eq}=1/(2\pi T_{ss})$=19.9Hz, wich is much lower than the crossover frequency obtained with both feedback compensations. The inductor current waveforms of Figures 9 and 10 show a larger magnitude of the inductor current overshoot compared to Figure 7. This is motivated by the higher current $i_{Cout}(t)=C_{out}V_{out,nom}/T_{ss}$ required to charge more rapidly the output capacitor when the 68nF soft start capacitance is adopted, which shortens the soft start time from 12ms to 8ms.

Experimental plots

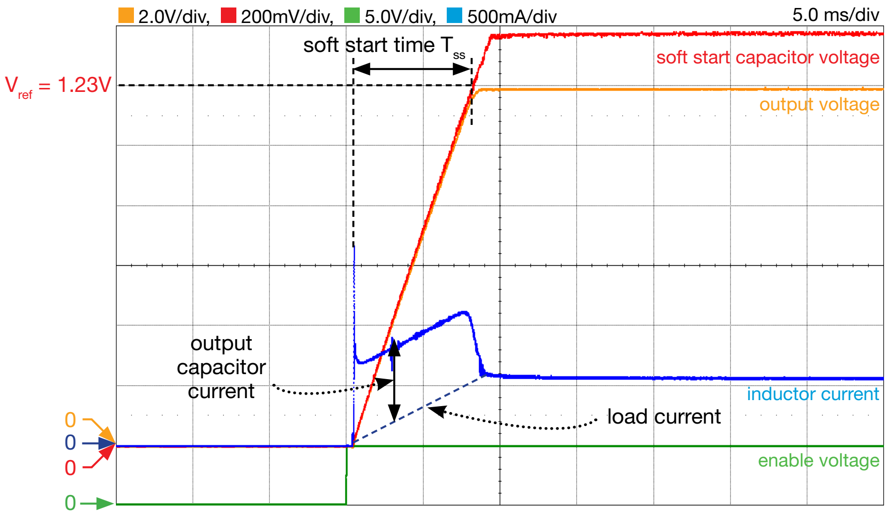


Figure 11. LM5118 Buck-Boost regulator soft start in BM, with R_{18} C_{22}, C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=0.5A, f_s=300kHz, R_{load}=22Ω, L=10µH, C_{ss}=68nF.

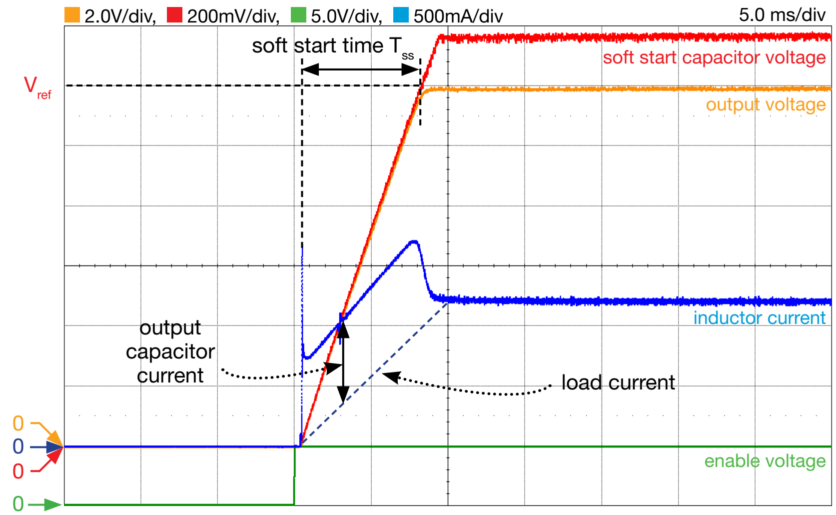


Figure 12. LM5118 Buck-Boost regulator soft start in BBM, with R_{18} C_{22}, C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=1.2A, f_s=300kHz, R_{load}=10Ω, L=10µH, C_{ss}=68nF.

The plots of Figures 11 and 12 show the soft-start of the LM5118 Buck-Boost regulator in Buck Mode with 0.5A and 1.2 load current, respectively. You see that the output voltage emulates perfectly the soft start capacitor voltage ramp in both cases. The slope of the inductor current with 0.5A load current is clearly lower than with 1.2A load current, as a lower final value of the load current has to be reached in the same soft start time, whereas the extra current required to charge up the output capacitor is the same.

Experimental plots

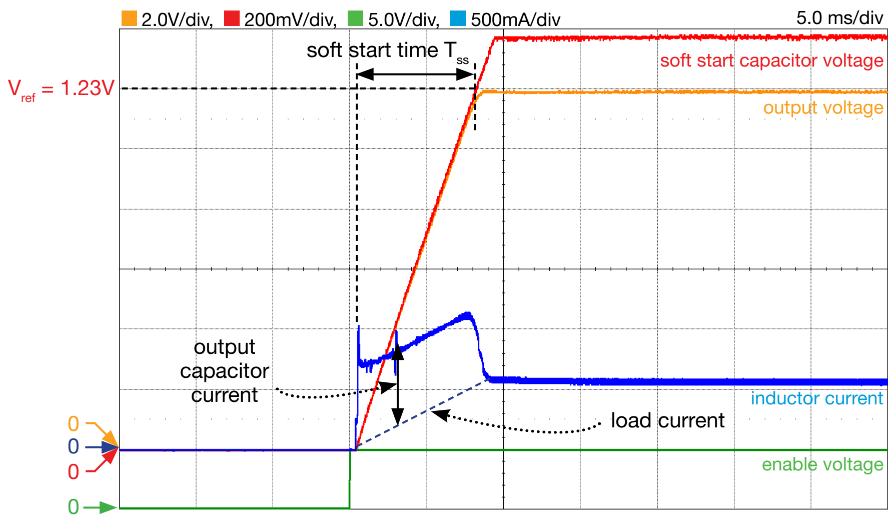


Figure 13. LM5118 Buck-Boost regulator soft start in BM, with R_{17}, C_{21}, C_{24} connected (low cross-over frequency): V_{in}=20V, I_{out}=0.5A, f_s=300kHz, R_{load}=22Ω, L=3.3µH, C_{ss}=68nF.

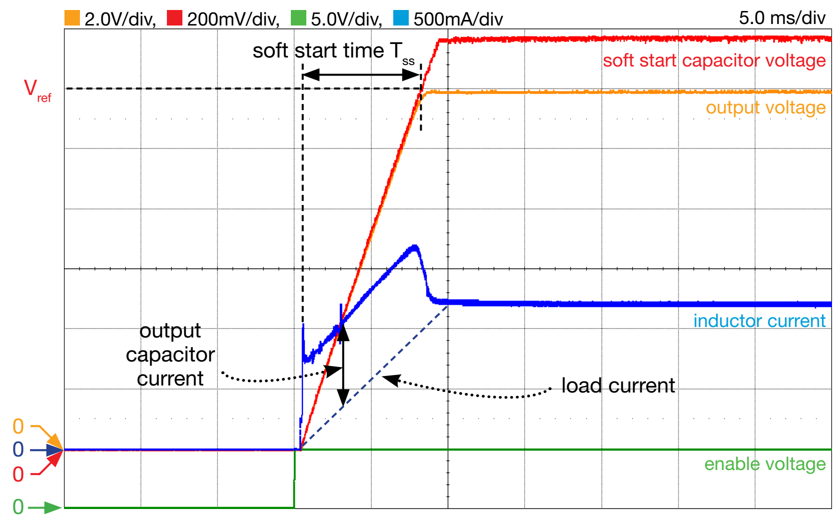


Figure 14. LM5118 Buck-Boost regulator soft start in BBM, with R_{17}, C_{21}, C_{24} connected (low cross-over frequency): V_{in}=20V, I_{out}=1.2A, f_s=300kHz, R_{load}=10Ω, L=3.3µH, C_{ss}=68nF.

The plots of Figures 13 and 14 show the soft-start of the LM5118 Buck-Boost regulator in Buck Mode with 0.5A and 1.2 load current, respectively, with 3.3µH inductance and relevant feedback compensation. You see that the output voltage emulates perfectly the soft start capacitor voltage ramp in both cases. The slope of the inductor current with 0.5A load current is clearly lower than with 1.2A load current, as a lower final value of the load current has to be reached in the same soft start time, whereas the extra current required to charge up the output capacitor is the same. These plots, compared to the plots of Figures 11 and 12, highlight that the results of the two soft starts are almost identical. In fact, the loop gain crossover frequency is sufficiently higher than the soft start equivalent frequency $f_{eq,ss}$ in both cases, despite of the different value of the inductance.

Experimental plots

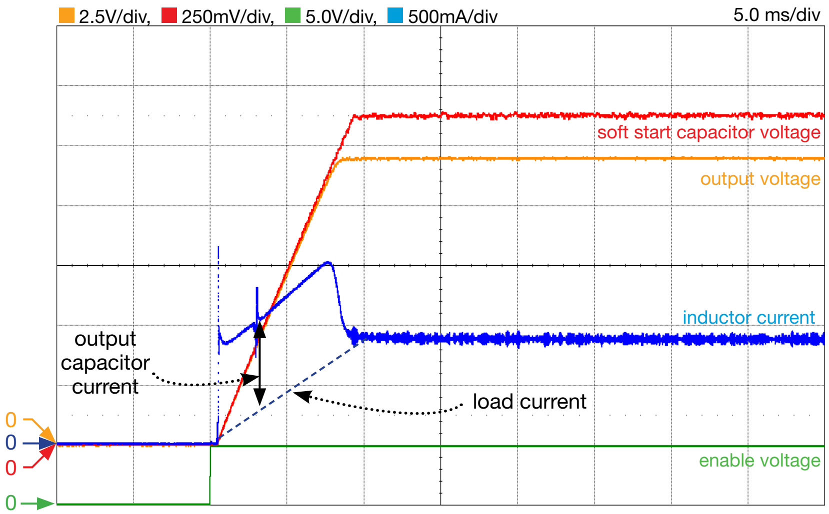


Figure 15. LM5118 Buck-Boost regulator soft start in BM: R_{18} C_{22}, C_{25} compensation connected, V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10μH, C_{ss}=68nF and C_{out}=2x180μF+2x47μF+2x0.47μF (J_{14} sh).

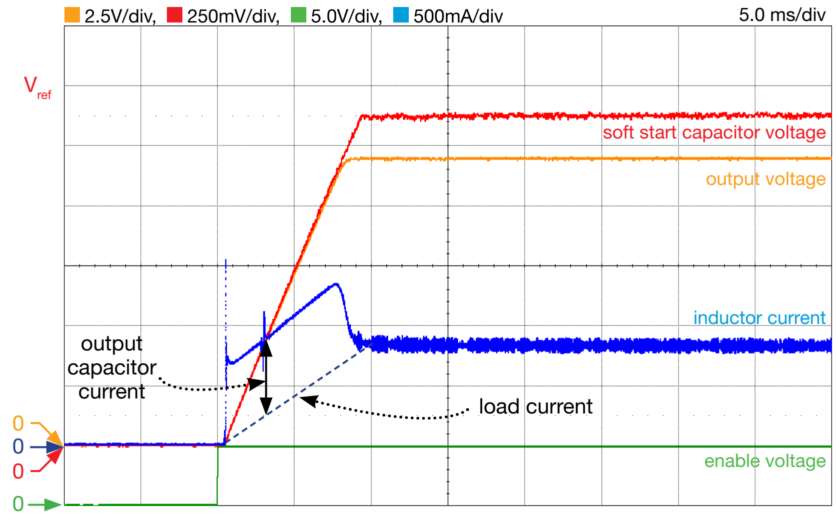


Figure 16. LM5118 Buck-Boost regulator soft start in BM: R_{18} C_{22}, C_{25} compensation connected, V_{in}=20V, I_{out}=0.8A, f_s=300kHz, R_{load}=15Ω, L=10μH, C_{ss}=68nF and C_{out}=2x180μF+2x0.47μF (J_{14} op).

You can make additional experiments to further analyze the soft start perfomance of the LM5118 Buck boost regutator. For example, you can disconnect the four 22μF capacitors C_7, C_{10}, C_{11} and C_{26}, by opening the jumper J_4, and observe about 25% reduction of the extra inductor current required to charge the output capacitor during the start up. The plots of Figures 15 and 16 show this effect.

Experimental plots

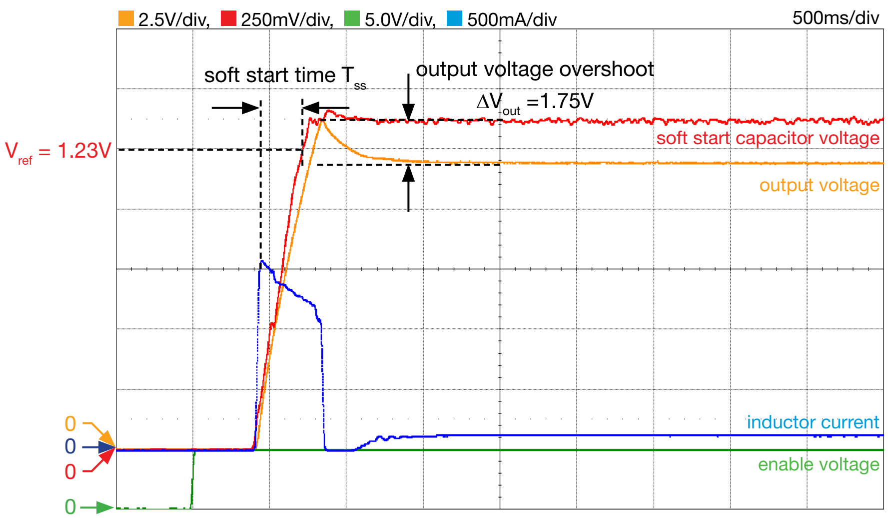


Figure 17. LM5118 Buck-Boost regulator soft start in BM, with R_{16} C_{20}, C_{23} connected (low cross-over frequency): V_{in}=20V, I_{out}=1.2A, f_s=300kHz, R_{load}=10Ω, L=3.3µH, C_{ss}=2.2nF.

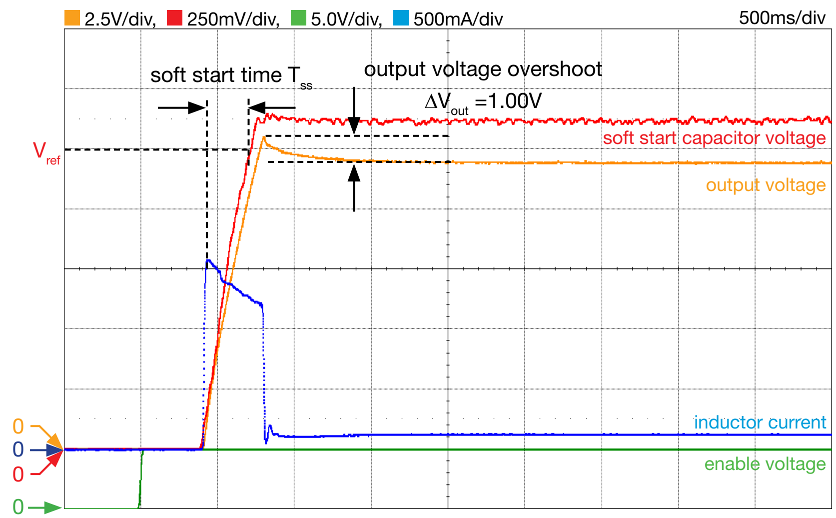


Figure 18. LM5118 Buck-Boost regulator soft start in BBM, with R_{18} C_{22} C_{25} connected (high cross-over frequency): V_{in}=20V, I_{out}=1.2A, f_s=300kHz, R_{load}=10Ω, L=3.3µH, C_{ss}=2.2nF.

You can also remove the 68nF capacitor C_{19} from the LM5118 board and replace it with a 2.2nF capacitor. This results in about 260µs soft start time T_{ss} and 600Hz equivalent ac frequency of the soft start capacitor voltage ramp slope. Figures 17 and 18 show the start up response of the LM5118 in these conditions. The perfect reference voltage tracking capability of the regulator is now lost. You can observe that the output voltage ramp up slope is lower than the reference voltage slope. Moreover, there is an overshoot in the output voltage before it settles to the 12V nominal value. In these conditions, the effect of a higher crossover frequency feedback compensation can be clearly detected. In fact, the output voltage overshoot magnitude is about 1.0V in the start up response shown in Figure 18, obtained with higher crossover compensation, whereas the output voltage overshoot magnitude is about 1.75V in the response shown in Figure 17, obtained with lower crossover compensation.

Appendix A

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[6] N.Femia, "*Feedback Injection-based Technique for Dynamic Load/Line Tests of DC Power Supplies - Part I: Theory*", in Proceedings of 17th IEEE Workshop on Control and Modeling for Power Electronics (COMPEL 2016), Trondheim, Norwey, June 2016

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[9] N.Femia, *Cost-Effective Test Methods Using TI-PMLK BUCK Boards*, http://www.ti.com/lit/ug/ssqu011/ssqu010.pdf

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[11] www.omicron-lab.com

[12] N.Femia, *TI-PMLK Boost Experiment Book*, http://www.ti.com/lit/ug/ssqu008/ssqu008.pdf

[13] N.Femia, *TI-PMLK Buck Experiment Book*, http://www.ti.com/lit/ug/ssqu007/ssqu007.pdf

Appendix B

Manufacturers websites

ASJ,	*http://www.asj.com.sg/*
AVX,	*http://www.avx.com/*
Bourns,	*http://www.bourns.com*
Coilcraft,	*http://www.coilcraft.com/*
Diodes Incorporated,	*http://www.diodes.com/*
Kemet,	*http://www.kemet.com/*
Murata,	*http://www.murata.com/*
Nippon Chemi-Con,	*http://www.chemi-con.co.jp/*
ON Semiconductor,	*http://www.onsemi.com/*
Panasonic,	*http://industrial.panasonic.com/*
Philips Lumileds,	*http://www.philipslumileds.com/*
Rohm Semiconductor,	*http://www.rohm.com/*
Samsung,	*http://www.samsungsem.com/*
Samwha,	*http://www.samwha.com/*
Taiyo Yuden,	*http://www.t-yuden.com/*
TDK,	*http://product.tdk.com/*
TE Connectivity,	*http://www.te.com/*
Texas Instruments,	*http://www.ti.com/*
TT Electronics,	*http://www.ttelectronics.com*
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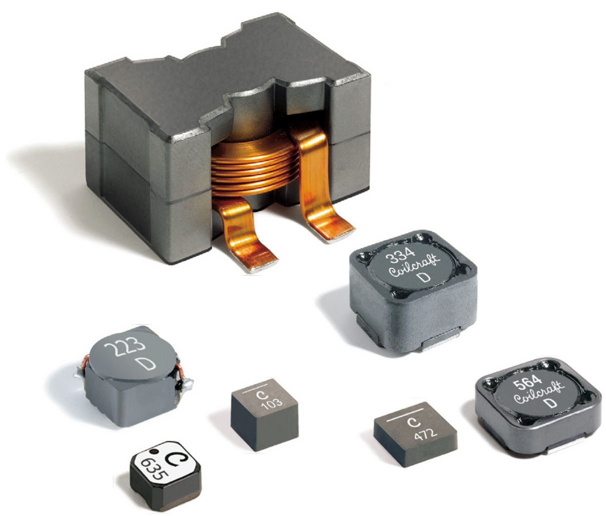

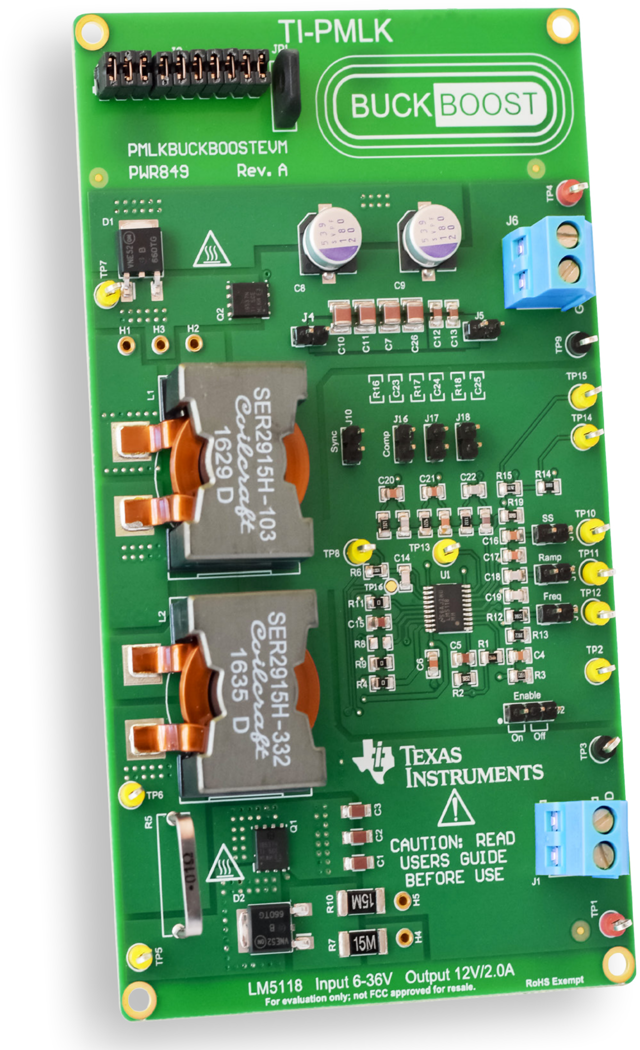

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TI Power Management Lab Kit
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