Laboratory Manual for Pulse-Width Modulated DC-DC Power Converters
LABORATORY MANUAL FOR PULSE-WIDTH MODULATED DC–DC POWER CONVERTERS
LABORATORY MANUAL FOR PULSE-WIDTH MODULATED DC–DC POWER CONVERTERS

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# Contents

Preface ix

Acknowledgments xiii

List of Symbols xv

## Part I  OPEN-LOOP PULSE-WIDTH MODULATED DC–DC CONVERTERS—STEADY-STATE AND PERFORMANCE ANALYSIS AND SIMULATION OF CONVERTER TOPOLOGIES

1 Boost DC–DC Converter in CCM—Steady-State Simulation 3

2 Efficiency and DC Voltage Transfer Function of PWM Boost DC–DC Converter in CCM 7

3 Boost DC–DC Converter in DCM—Steady-State Simulation 11

4 Efficiency and DC Voltage Transfer Function of PWM Boost DC–DC Converter in DCM 15

5 Open-Loop Boost AC–DC Power Factor Corrector—Steady-State Simulation 19

6 Buck DC–DC Converter in CCM—Steady-State Simulation 23

7 Efficiency and DC Voltage Transfer Function of PWM Buck DC–DC Converter in CCM 27

8 Buck DC–DC Converter in DCM—Steady-State Simulation 31

9 Efficiency and DC Voltage Transfer Function of PWM Buck DC–DC Converter in DCM 35
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>High-Side Gate-Drive Circuit for Buck DC–DC Converter</td>
<td>39</td>
</tr>
<tr>
<td>11</td>
<td>Quadratic Buck DC–DC Converter in CCM—Steady-State Simulation</td>
<td>41</td>
</tr>
<tr>
<td>12</td>
<td>Buck–Boost DC–DC Converter in CCM—Steady-State Simulation</td>
<td>45</td>
</tr>
<tr>
<td>13</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Buck–Boost DC–DC Converter in CCM</td>
<td>49</td>
</tr>
<tr>
<td>14</td>
<td>Buck–Boost DC–DC Converter in DCM—Steady-State Simulation</td>
<td>53</td>
</tr>
<tr>
<td>15</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Buck–Boost DC–DC Converter in DCM</td>
<td>57</td>
</tr>
<tr>
<td>16</td>
<td>Flyback DC–DC Converter in CCM—Steady-State Simulation</td>
<td>61</td>
</tr>
<tr>
<td>17</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Flyback DC–DC Converters in CCM</td>
<td>65</td>
</tr>
<tr>
<td>18</td>
<td>Multiple-Output Flyback DC–DC Converter in CCM</td>
<td>69</td>
</tr>
<tr>
<td>19</td>
<td>Flyback DC–DC Converter in DCM—Steady-State Simulation</td>
<td>73</td>
</tr>
<tr>
<td>20</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Flyback DC–DC Converter in DCM</td>
<td>77</td>
</tr>
<tr>
<td>21</td>
<td>Forward DC–DC Converter in CCM—Steady-State Simulation</td>
<td>81</td>
</tr>
<tr>
<td>22</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Forward DC–DC Converter in CCM</td>
<td>85</td>
</tr>
<tr>
<td>23</td>
<td>Forward DC–DC Converter in DCM—Steady-State Simulation</td>
<td>89</td>
</tr>
<tr>
<td>24</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Forward DC–DC Converter in DCM</td>
<td>93</td>
</tr>
<tr>
<td>25</td>
<td>Half-Bridge DC–DC Converter in CCM—Steady-State Simulation</td>
<td>97</td>
</tr>
<tr>
<td>26</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Half-Bridge DC–DC Converter in CCM</td>
<td>101</td>
</tr>
<tr>
<td>27</td>
<td>Full-Bridge DC–DC Converter in CCM—Steady-State Simulation</td>
<td>105</td>
</tr>
<tr>
<td>28</td>
<td>Efficiency and DC Voltage Transfer Function of PWM Full-Bridge DC–DC Converters in CCM</td>
<td>109</td>
</tr>
</tbody>
</table>
## Part II  CLOSED-LOOP PULSE-WIDTH MODULATED DC–DC CONVERTERS—TRANSIENT ANALYSIS, SMALL-SIGNAL MODELING, AND CONTROL

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>Design of the Pulse-Width Modulator and the PWM Boost DC–DC Converter in CCM</td>
<td>115</td>
</tr>
<tr>
<td>30</td>
<td>Dynamic Analysis of the Open-Loop PWM Boost DC–DC Converter in CCM for Step Change in the Input Voltage, Load Resistance, and Duty Cycle</td>
<td>119</td>
</tr>
<tr>
<td>31</td>
<td>Open-Loop Control-to-Output Voltage Transfer Function of the Boost Converter in CCM</td>
<td>123</td>
</tr>
<tr>
<td>32</td>
<td>Root Locus and 3D Plot of the Control-to-Output Voltage Transfer Function</td>
<td>129</td>
</tr>
<tr>
<td>33</td>
<td>Open-Loop Input-to-Output Voltage Transfer Function of the Boost Converter in CCM</td>
<td>133</td>
</tr>
<tr>
<td>34</td>
<td>Open-Loop Small-Signal Input and Output Impedances of the Boost Converter in CCM</td>
<td>137</td>
</tr>
<tr>
<td>35</td>
<td>Feedforward Control of the Boost DC–DC Converter in CCM</td>
<td>141</td>
</tr>
<tr>
<td>36</td>
<td>P, PI, and PID Controller Design</td>
<td>145</td>
</tr>
<tr>
<td>37</td>
<td>P, PI, and PID Controllers: Bode and Transient Analysis</td>
<td>149</td>
</tr>
<tr>
<td>38</td>
<td>Transfer Functions of the Pulse-Width Modulator, Boost Converter Power Stage, and Feedback Network</td>
<td>153</td>
</tr>
<tr>
<td>39</td>
<td>Closed-Loop Control-to-Output Voltage Transfer Function with Unity-Gain Control</td>
<td>157</td>
</tr>
<tr>
<td>40</td>
<td>Simulation of the Closed-Loop Boost Converter with Proportional Control</td>
<td>161</td>
</tr>
<tr>
<td>41</td>
<td>Voltage-Mode Control of Boost DC–DC Converter with Integral-Double-Lead Controller</td>
<td>165</td>
</tr>
<tr>
<td>42</td>
<td>Control-to-Output Voltage Transfer Function of the Open-Loop Buck DC–DC Converter</td>
<td>169</td>
</tr>
<tr>
<td>43</td>
<td>Voltage-Mode Control of Buck DC–DC Converter</td>
<td>173</td>
</tr>
<tr>
<td>44</td>
<td>Feedforward Control of the Buck DC–DC Converter in CCM</td>
<td>179</td>
</tr>
<tr>
<td>Part III</td>
<td>SEMICONDUCTOR MATERIALS AND POWER DEVICES</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Temperature Dependence of Si and SiC Semiconductor Materials 187</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Dynamic Characteristics of the PN Junction Diode 191</td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>Characteristics of the Silicon and Silicon-Carbide PN Junction Diodes 195</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>Analysis of the Output and Switching Characteristics of Power MOSFETs 199</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Short-Channel Effects in MOSFETs 201</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Gallium-Nitride Semiconductor: Material Properties 205</td>
<td></td>
</tr>
</tbody>
</table>

APPENDICES 209

A Design Equations for Continuous-Conduction Mode 211
B Design Equations for Discontinuous-Conduction Mode 215
C Simulation Tools 219
D MOSFET Parameters 231
E Diode Parameters 233
F Selected MOSFETs Spice Models 235
G Selected Diodes Spice Models 237
H Physical Constants 239
I Format of Lab Report 241

Index 245
Preface

The Laboratory Manual for Pulse-Width Modulated DC–DC Power Converters is intended to aid undergraduate and graduate students of electrical engineering, practicing engineers, scientists, and circuit designers to have a grasp on designing and simulating a variety of fundamental and advanced power electronic circuits. The manual enables users to get accustomed to different simulation tools such as MATLAB®, Synopsys SABER®, LTSpice®, PLECS®, or any other Spice-based circuit simulation platforms. The approach presented in this manual will enhance a student’s understanding of different power electronic converters and also gain knowledge in great depth on performing circuit simulations; a characteristic needed for a career in electrical engineering.

This manual is a supplementary material to the successful edition of the textbook Pulse-width Modulated DC–DC Power Converters, Second Edition, authored by Prof. Marian K. Kazimierczuk. The lab manual complements the content of the textbook and the combination of the two is a one-stop arrangement for students and instructors to gain the most about power electronic circuits and their simulation. This book features the following attributes:

i. Unique in the market of textbooks for power electronics.
ii. Can be adopted as a supplementary material for any commercially available textbooks on power electronics as well as classnotes.
iii. Can be used for distance-learning power electronic course or e-learning.
iv. The software-oriented approach makes it convenient for students to have take-home assignments.
v. Simple and easy-to-understand procedure set.
vi. Provides a quick overview of various power converters and components.

The purpose of the Laboratory Manual for Pulse-Width Modulated DC–DC Power Converters is to provide a comprehensive instruction set for the following:

a. To design and simulate various topologies of power electronic dc–dc converters such as boost and boost-derived, buck and buck-derived, flyback, forward, half-bridge, and full-bridge converter topologies, operating in continuous-conduction mode or discontinuous-conduction mode.
b. To simulate the small-signal models of the power electronic circuits and to understand the different small-signal characteristics of boost and buck converters operating in continuous-conduction mode.
c. To understand the properties of silicon, silicon-carbide, and gallium-nitride power MOSFETs used in power electronic applications.

The topics presented in this lab manual have been thoughtfully considered, keeping in mind the benefits it offers to the students. The primary author of this lab manual has been teaching specialized graduate-level courses in power electronics for more than 25 years. Since then, consistent effort has been put into creating equally interesting and accurate lab curricula for the students. The outcome of that dedication has been this lab manual. The experiments in this manual have been tested and updated regularly for technical correctness and clarity in the presentation style. The authors of this book recommend the below instructions for instructors and students in making the best use of this manual.

**For Instructors**

Instructors involved in teaching power electronic courses can adopt this lab manual as a required course material. The lab manual consists of three parts:

- **PART I—Open-Loop Pulse-Width Modulated DC–DC Power Converters**
- **PART II—Closed-Loop Pulse-Width Modulated DC–DC Power Converters**
- **PART III—Semiconductor Materials and Power Devices**

Part I consists of 28 lab experiments. Part II has 16 lab experiments. Part III offers 6 lab experiments with several subsections. For an undergraduate power electronic course offered once an academic year, instructors can adopt selected lab topics from all of the three parts. For graduate programs offering specialized power electronic courses and taught for more than one semester, instructors may plan to dedicate a single part for every semester. The post-lab exercise will aid in summarizing the lab activity that was performed and provides a background for the consecutive labs. The students must be encouraged to follow the format of lab report at the end of the Appendix. Following such a format will aid in improving the students’ technical communication and problem solving skills as well as their professional writing capabilities.

**For Students**

The lab manual assumes that the student is familiar with general circuit analysis techniques, electronic circuits, and the basic know-how of simulation tools. Every lab topic includes a pre-lab section. Students are encouraged to understand the circuit operation, calculate the component values, and also understand the design process of the converter under consideration. It is expected that the students follow every step in the procedure section for successful completion of the lab topic. The quick design section provides data about the component values and component selection that students can use for rapid verification. The Appendix has been made very resourceful and provides the following information:

a. Detailed summary of design equations for buck, boost, buck–boost, flyback, forward, half-bridge, and full-bridge converter in continuous-conduction mode and discontinuous-conduction mode.
b. Instructions on using MATLAB®, Synopsys SABER®, and other Spice-based simulation tools.
c. Spice models of several power diodes and power MOSFETs needed for component selection.
d. A summary of physical constants, values of different properties of silicon (Si), silicon-carbide (SiC), and gallium-nitride (GaN) semiconductor materials and power devices.
e. Format and guidelines to prepare a well-organized lab report.
Acknowledgments

Throughout the entire course of this project, the support provided by John Wiley and Sons, Ltd was exceptional. We wish to express our sincere thanks to Peter Mitchell, Publisher, Electrical Engineering; Ella Mitchell, Associate Commissioning Editor; and Liz Wingett, Project Editor for their cooperation. Our thanks are also to the team under Baljinder Kaur at Aptara Co. for their patience and tireless efforts in organizing the editing process. We would also like to extend our thanks and great appreciation to our families for their support.

Selected experiments in this lab manual were administered to power electronic graduate students at Wright State University. The results of these experiments performed by the students have been recorded continuously for better accuracy and improvement in the instruction set. We would like to thank the efforts of several students who were directly or indirectly involved in making this manuscript complete.

We have sincerely attempted at making this edition of the lab manual error-free so that students gain a better understanding of the course material. The authors would welcome and greatly appreciate readers’ suggestions, corrections for improvements of the technical content as well as the presentation style, and ideas for newer topics, which can be implemented in possible future editions.

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List of Symbols

\( A \) Transfer function of forward path in negative feedback system
\( A_i \) Inductor-to-load current transfer function
\( A_J \) Cross-sectional area of junction
\( BW \) Bandwidth
\( C \) Filter capacitance
\( C_b \) Blocking capacitance
\( C_c \) Coupling capacitance
\( C_{ds} \) Drain–source capacitance of MOSFET
\( C_{gd} \) Gate–drain capacitance of MOSFET
\( C_{gs} \) Gate–source capacitance of MOSFET
\( C_{iss} \) MOSFET input capacitance at \( V_{DS} = 0 \), \( C_{iss} = C_{gs} + C_{gd} \)
\( C_{min} \) Minimum value of filter capacitance \( C \)
\( C_o \) Transistor output capacitance
\( C_{oss} \) MOSFET output capacitance at \( V_{GD} = 0 \), \( C_{oss} = C_{gs} + C_{ds} \)
\( C_{ox} \) Oxide capacitance per unit area
\( C_{rss} \) MOSFET transfer capacitance, \( C_{rss} = C_{gd} \)
\( c \) Speed of light
\( D \) DC component of on-duty cycle of switch
\( d \) AC component of on-duty cycle of switch
\( D_m \) Amplitude of small-signal component of on-duty cycle of switch
\( d_T \) Total on-duty cycle of switch
\( ESR \) Equivalent series resistance of capacitors and inductors
\( f_c \) Gain-crossover frequency
\( f_z \) Frequency of zero of transfer function
\( f_0 \) Corner frequency
\( f_p \) Frequency of pole of transfer function
\( f_s \) Switching frequency
\( f_{-180} \) Phase-crossover frequency
\( I_D \) Average diode current
\( I_{DM} \) Peak diode current
\( I_{Drms} \) rms value of diode current
\( I_I \) DC input current of converter
\( I_L \) Average current through inductor \( L \)
\( I_{LB} \) Average current through inductor \( L \) at CCM/DCM boundary
List of Symbols

\( I_O \)  DC output current of converter
\( I_{O_{\text{max}}} \)  Maximum value of dc load current \( I_0 \)
\( I_{O_{\text{min}}} \)  Minimum value of dc load current \( I_0 \)
\( I_{SM} \)  Peak switch current
\( i_o \)  AC component of load current
\( i_C \)  Current through filter capacitor \( C \)
\( i_D \)  Diode current
\( i_L \)  Current through inductor \( L \)
\( i_O \)  Total load current
\( i_S \)  Switch current
\( k \)  Boltzmann constant
\( L \)  Inductance, Channel length
\( L_e \)  Effective channel length
\( L_n \)  Electron diffusion length
\( L_p \)  Hole diffusion length
\( L_m \)  Magnetizing inductance of transformer
\( L_{max} \)  Maximum inductance \( L \) for DCM operation
\( L_{min} \)  Minimum inductance \( L \) for CCM operation
\( M_{vDC} \)  DC voltage transfer function of converter
\( M_v \)  Open-loop input-to-output voltage function of converter
\( M_{\text{icl}} \)  Closed-loop input-to-output voltage function of converter
\( M_{id} \)  Open-loop input voltage-to-inductor current transfer function
\( M_{vo} \)  Open-loop input-to-output voltage function of converter at \( f = 0 \)
\( m_e \)  Mass of free electron
\( m_e^* \)  Effective mass of electron
\( m_h \)  Mass of hole
\( m_h^* \)  Effective mass of hole
\( N_A \)  Concentration of acceptors
\( N_D \)  Concentration of donors
\( N_p \)  Number of turns of primary winding
\( N_s \)  Number of turns of secondary winding
\( n \)  Transformer turns ratio, electron concentration density
\( n_i \)  Intrinsic carrier concentration
\( n_{pO} \)  Thermal equilibrium minority electron concentration
\( p_{pO} \)  Thermal equilibrium minority hole concentration
\( PM \)  Phase margin
\( P_I \)  DC input power of converter
\( P_{LS} \)  Overall power dissipation of converter
\( PM \)  Phase margin
\( P_O \)  DC output power of converter
\( P_{RF} \)  Conduction loss in diode forward resistance \( R_F \)
\( P_{rC} \)  Conduction loss in filter capacitor ESR
\( P_{VF} \)  Conduction loss in diode offset voltage \( V_F \)
\( p \)  Hole concentration
\( Q \)  Quality factor
List of Symbols

- $Q_g$: Gate charge
- $q$: Magnitude of electron charge
- $r$: Total parasitic resistance
- $R_{DR}$: Resistance of drift region
- $R_F$: Diode forward resistance
- $R_L$: DC load resistance
- $R_{LB}$: DC load resistance at CCM/DCM boundary
- $R_{L,\text{max}}$: Maximum value of load resistance $R_L$
- $R_{L,\text{min}}$: Minimum value of load resistance $R_L$
- $r_{DS}$: Equivalent series resistance (ESR) of filter capacitor
- $r_{DS}$: On-resistance of MOSFET
- $e$: Electron charge
- $S_{\text{max}}$: Maximum percentage overshoot
- $T$: Switching period, Loop gain
- $T_A$: Ambient temperature
- $T_c$: Voltage transfer function of controller
- $T_{cl}$: Closed-loop control-to-output transfer function
- $T_J$: Junction temperature
- $T_m$: Transfer function of pulse-width modulator
- $T_p$: Open-loop control-to-output transfer function
- $T_{po}$: Open-loop control-to-output transfer function at $f = 0$
- $t_f$: Fall time
- $t_r$: Rise time
- $t_{rr}$: Reverse recovery time
- $V_{bi}$: Built-in potential
- $V_C$: DC component of control voltage
- $V_{cpp}$: Peak-to-peak ripple voltage of the filter capacitance
- $V_E$: DC component of error voltage
- $V_I$: Gate-to-source threshold voltage
- $V_{BD}$: Breakdown voltage
- $V_{BR}$: Reverse blocking (breakdown) voltage
- $V_{DM}$: Reverse peak voltage of diode
- $V_{DS}$: Drain–source dc voltage of MOSFET
- $V_{DSS}$: Drain–source breakdown voltage of MOSFETs
- $V_F$: Diode offset voltage, dc component of feedback voltage
- $V_I$: DC component of input voltage of converter
- $V_O$: DC output voltage of converter
- $V_R$: DC reference voltage
- $V_{r}$: Peak-to-peak value of output ripple voltage
- $V_{r,\text{cpp}}$: Peak-to-peak ripple voltage across ESR
- $V_{SM}$: Peak switch voltage
- $V_T$: Thermal voltage
- $V_{Tm}$: Peak ramp voltage of pulse-width modulator
- $v_C$: Total control voltage
- $v_c$: AC component of control voltage
- $V_{DS}$: Drain–source voltage of MOSFET
$v_E$  Total error voltage
$v_F$  Total feedback voltage
$v_e$  AC component of error voltage
$v_d$  Average drift velocity
$v_f$  AC component of feedback voltage
$v_L$  Voltage across inductance $L$
$v_i$  AC component of converter input voltage
$v_o$  AC component of converter output voltage
$v_{sat}$  Saturation velocity of carriers
$v_r$  AC component of reference voltage
$v_{rc}$  Voltage across ESR of filter capacitor
$v_{th}$  Thermal velocity of electron
$v_{sat}$  Saturated average drift velocity
$W$  Channel width
$W_C$  Energy stored in capacitor
$w_L$  Energy stored in inductor
$Z_i$  Open-loop input impedance of converter
$Z_o$  Open-loop output impedance of converter
$\beta$  Transfer function of feedback network
$\Delta i_L$  Peak-to-peak of inductor ripple current
$\eta$  Efficiency of converter
$\theta$  Thermal resistance, Mobility degradation coefficient
$\mu$  Carrier mobility
$\mu_p$  Mobility of holes
$\mu_n$  Mobility of electrons
$\xi$  Damping ratio
$\rho$  Resistivity
$\sigma$  Conductivity, Damping factor
$\tau$  Minority carrier lifetime, Time constant
$\tau_n$  Electron lifetime
$\tau_p$  Hole lifetime
$\phi$  Phase of transfer function, Magnetic flux
$\omega$  Angular frequency
$\omega_c$  Unity-gain angular crossover frequency
$\omega_0$  Corner angular frequency
$\omega_p$  Angular frequency of simple pole
$\omega_z$  Angular frequency of simple zero
Part I

Open-Loop Pulse-Width Modulated DC–DC Converters—Steady-State and Performance Analysis and Simulation of Converter Topologies
1

Boost DC–DC Converter in CCM—Steady-State Simulation

Objectives

The objectives of this lab are:

- To design a pulse-width modulated (PWM) boost dc–dc converter operating in continuous-conduction mode (CCM) for the design specifications provided.
- To simulate the boost converter on a circuit simulator and to analyze its characteristics in steady state.
- To determine the overall losses and the efficiency of the boost converter.

Specifications

The specifications of the boost converter are as provided in Table 1.1.

Pre-lab

For the specifications provided, find the values of all the components and parameters for the boost dc–dc converter operating in CCM using the relevant design equations provided in Table A.1 in Appendix A.

Quick Design

Choose:

\[ L = 20 \, \text{mH}, \quad ESR \, \text{of the inductor} \quad r_L = 2.1 \, \Omega, \quad R_{L_{\text{min}}} = 1.778 \, \text{k} \Omega, \quad R_{L_{\text{max}}} = 35.6 \, \text{k} \Omega, \quad D_{\text{min}} = 0.579, \quad D_{\text{nom}} = 0.649, \quad D_{\text{max}} = 0.714, \quad C = 1 \, \mu \text{F}, \quad ESR \, \text{of the capacitor} \quad r_C = 1 \, \Omega. \]
Table 1.1 Parameters and their values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum dc input voltage</td>
<td>$V_{I_{\text{min}}}$</td>
<td>127 V</td>
</tr>
<tr>
<td>Nominal dc input voltage</td>
<td>$V_{I_{\text{nom}}}$</td>
<td>156 V</td>
</tr>
<tr>
<td>Maximum dc input voltage</td>
<td>$V_{I_{\text{max}}}$</td>
<td>187 V</td>
</tr>
<tr>
<td>DC output voltage</td>
<td>$V_{O}$</td>
<td>400 V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_s$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Maximum output current</td>
<td>$I_{O_{\text{max}}}$</td>
<td>0.225 A</td>
</tr>
<tr>
<td>Minimum output current</td>
<td>$I_{O_{\text{min}}}$</td>
<td>5% of $I_{O_{\text{max}}}$</td>
</tr>
<tr>
<td>Output voltage ripple</td>
<td>$V_r$</td>
<td>&lt; 0.01$V_{O}$</td>
</tr>
</tbody>
</table>

MOSFET: International Rectifier IRF430 n-channel power MOSFET with $V_{DSS} = 500$ V, $I_{SM} = 4.5$ A, $r_{DS} = 1.8$ Ω at $T = 25^\circ$C, $C_o = 135$ pF, and $V_t = 4$ V.

Diode: ON Semiconductor MUR1560 with $V_{R_{\text{RM}}} = 600$ V, $I_F = 15$ A, $R_F = 17.1$ mΩ, and $V_F = 1.5$ V.

Procedure

A. *Simulation of the Boost Converter and its Analysis in Steady State*

1. Construct the circuit of the boost converter shown in Figure 1.1 on the circuit simulator. Name the nodes and components for convenience. Enter the values of all the components.
2. Initially, simulate the converter at $V_I = V_{I_{\text{nom}}} = 156$ V, $R_L = R_{L_{\text{min}}} = 1.778$ kΩ, and $D = D_{\text{nom}} = 0.649$. Connect a pulse voltage source in order to provide the gate-to-source voltage at the MOSFET gate and source terminals. Set time period = 10 μs, duty cycle/width = 0.649, and amplitude = 12 V. Let the rise time and fall time be equal to zero (optional).
3. Set simulation type to transient analysis. Set end time = 10 ms and time step = 0.1 μs. Run the simulation.
4. Plot the following waveforms after successful completion of the simulation. You may display the waveforms on different figure windows for better clarity.
   - Gate-to-source voltage $v_{GS}$, drain-to-source voltage $v_{DS}$, and diode voltage $v_D$.
   - Output voltage $v_O$, output current $i_O$, and output power $P_O$.
   - Inductor current $i_L$, diode current $i_D$, and MOSFET current $i_S$.
   Zoom in to display the steady-state region.

Figure 1.1 Circuit diagram of the PWM boost dc–dc converter.
5. Observe the inductor current waveform to ensure whether the current is in CCM. If the current is not in CCM, then increase the value of the inductor and repeat the simulation.

6. For the above-mentioned waveforms, measure:
   - The average and peak-to-peak values of the current through the inductor \( L \).
   - The maximum and average values of the voltage across the MOSFET \( S \).
   - The minimum and average values of the voltage across the diode \( D_0 \).
   - The maximum and average values of the currents through the MOSFET and the diode.
   
   Ensure that the values obtained above match the desired specifications. Should there be any deviation in the values, adjust the value of the duty cycle accordingly.

7. Repeat the steps above with duty cycle \( D_{min} = 0.579 \) and input voltage \( V_{Imax} = 187 \) V. Also, repeat for a duty cycle of \( D_{max} = 0.714 \) and an input voltage of \( V_{Inom} = 127 \) V.

B. Simulation of the Boost Converter to Determine the Power Losses and Overall Efficiency

1. Set up the converter to operate at the nominal operating condition, that is, at \( D = D_{nom} \) and \( V_I = V_{Inom} \). Let \( R_L = R_{Lmin} \) such that the converter is delivering maximum output power.

2. Set the simulation type to transient analysis and perform the simulation.

3. Plot the waveforms of the input power \( p_I \) and the output power \( p_O \). Zoom in to display the steady-state region.

4. Measure the average values of the input power and the output power. If the input power is negative, then consider only the magnitude of the average value of the input power.

5. Calculate the efficiency of the converter using \( \eta = P_O / P_I \), where \( P_O \) is the average value of the output power and \( P_I \) is the average value of the input power, respectively.

6. This section may be repeated by plotting the power waveforms of all the components and then estimating their average values. All the power losses can be added to give the total power loss in the converter. Further, the efficiency can be estimated using \( \eta = P_O / (P_{LS} + P_I) \), where \( P_O \) is the average value of the output power and \( P_{LS} \) is the sum of the average values of the power loss in individual components.

7. Repeat the above-mentioned activities in this section for \( R_L = R_{Lmax} \) to determine the efficiency at minimum output power.

**Post-lab Questions**

1. Determine through simulations the maximum value of load resistance beyond which the converter operates in discontinuous-conduction mode?

2. Draw the waveforms of the inductor current for the input voltage at \( V_{Imin}, V_{Inom}, \) and \( V_{Imax} \).

3. Draw the waveforms of the diode current, current through the filter capacitor, and current through the load resistor. Describe the nature of the three currents in terms of their shape and peak-to-peak values.

4. Draw the waveforms of the voltages across the capacitor and the equivalent series resistance of the capacitor.

5. Identify the component in the converter, which exhibits the highest power loss. Provide a proper reason for your answer.
Efficiency and DC Voltage Transfer Function of PWM Boost DC–DC Converter in CCM

Objectives

The objectives of this lab are:

- To design a PWM boost dc–dc converter in CCM for the given specifications.
- To analyze the variations in the efficiency of the lossy boost converter at different load resistances and input voltages.
- To determine the effect of duty cycle on the efficiency and steady-state dc voltage transfer function.

Theory

The steady-state dc voltage transfer function of a converter is

\[ M_{V_{DC}} = \frac{V_O}{V_I}. \]  \hspace{1cm} (2.1)

The overall converter efficiency is

\[ \eta = \frac{N_n}{D_n}. \] \hspace{1cm} (2.2)