Experimental evaluation setup to Measure Inductor Current in a Buck Converter

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This thesis is presented as part of Degree of Master of Science in Electrical Engineering

Blekinge Institute of Technology
May 2011
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>3E</td>
<td>Energy management, Enhanced performance, End-user value</td>
</tr>
<tr>
<td>CD</td>
<td>Compact Disc</td>
</tr>
<tr>
<td>CD-ROM</td>
<td>Compact Disc – Read Only Memory</td>
</tr>
<tr>
<td>CMM</td>
<td>Configuration Monitoring Management</td>
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<tr>
<td>CTRL</td>
<td>Control</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DVD</td>
<td>Digital Versatile Disc</td>
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<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>IBC</td>
<td>Intermediate Bus Converter</td>
</tr>
<tr>
<td>MB</td>
<td>Megabytes</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PMBus</td>
<td>Power Management Bus</td>
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<tr>
<td>POL</td>
<td>Point of Load</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>SW</td>
<td>Software</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>VADJ</td>
<td>Voltage output Adjust</td>
</tr>
<tr>
<td>VCC</td>
<td>Positive Supply Voltage</td>
</tr>
<tr>
<td>VDC</td>
<td>Volt Direct Current</td>
</tr>
<tr>
<td>VOUT</td>
<td>Output Voltage</td>
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Acknowledgement

First and foremost, we would like to express our sincere gratitude to GOD (Sri Shiridi Saibaba) for blessing us with the potential and ability to work on this master thesis.

We express our sincere gratitude to our Senior lecturer Mr. Anders Hultgren for his guidance and constant encouragement throughout the project work. We are very grateful to him for providing us his valuable time through various sessions to discuss the issues related to our thesis work which enabled us to take this thesis to productive completion. We are thankful to Ericsson Company for providing challenging platform and experimental setup to work.

We would like to thank Mr. Kristian Nilsson for his guidance and support throughout the project in the laboration.

We would like to thank Mr. Shayan Haider for helping us with the measurements in the lab.

Special thanks to Mr. Mikael Asman, program manager for DDP in SWEDEN, for his valuable suggestions and guidance during the entire course work.

We would like to thank Mr. Gurudutt Kumar Velpula, international coordinator for DDP, for providing us the opportunity to study in BTH, SWEDEN and also we would like to thank Dr. Madhavilatha, Coordinator for DDP, JNTU.

We would like to convey our heartful thanks to all the professors of BTH and JNTU for their immense help and moral support in completing our course work successfully.

We are very grateful to our parents, our sisters and brothers and fellow students for their support and constant encouragement.
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Chapter 1
Introduction

In today’s consumer market, battery-operated portable electronic devices such as cellular phones, personal digital assistants (PDAs), and other palm-size devices are in great demand. A device that accepts a regulated or unregulated DC (Direct Current is the unidirectional flow of the electric charge) input voltage and produces a DC output at a level that usually differs from the input is known as DC/DC Converters. At times, the converter may have the same input and output levels to provide noise isolation or power bus regulation. Power management ICs (Integrated Circuit is a semiconductor wafer on which thousands or millions of tiny resistors, capacitors, and transistors are fabricated), such as the highly efficient low-voltage switch-mode DC–DC converters, are mandatory in these devices for maximizing the system run time. In order to decrease the size and weight of these devices, efficiency of the power modules is essential and the cost factor is also considered. As a result, the trend is to focus on the implementation of low-power power converters such that power management and mixed-signal circuitries can be fabricated on the same chip for low-power applications.

The reliability of all electronic equipment is underpinned by the reliability of its power supply system. In this field, Ericsson Power Modules is recognized as a leading supplier of miniaturized and high-density DC/DC power modules for distributed power architectures. Used throughout the world, these products combine the highest efficiency currently available with unprecedented reliability.

Ericsson products are developed to align with their customers’ requirements. They develop cost-efficient and flexible product platforms based on proven solutions and standard components. Ericsson’s DC/DC Power modules are the ideal building blocks for the highest system performance, and are used in advance applications such as radio base stations and switches/routers.

Today the current company, Ericsson Power Modules, is a part of Ericsson. But the story begins back in 1977, when Ericsson Power Division began advanced research into high frequency switching DC/DC converters.

A simplified electrical model of a converter power train, i.e., components transmitting power is given in Figure 1. The converter input is a voltage source \( V_{in} \) connected via a switch transistor \( T \). The converter consists mainly of an inductor modeled in Figure 1 by the resistance \( R_L \) and inductance \( L \). An output capacitor is modelled by the capacitance \( C \) and resistance \( R \).

The operation of the below circuit is simple, with an inductor and two switches usually a transistor (is controlled by a pulse width modulated signal about 300 kHz) and a diode that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging the inductor into the load.
The circuit operates in continuous mode if the current through the inductor \( (I_L) \) never falls to zero. In this mode, the operation principle is described as:

- When the switch below is closed (on-state), the voltage across the inductor is \( V_L = V_{IN} - V_{OUT} \). The current through the inductor rises linearly. As the diode is reverse-biased by the voltage source V, no current flows through it.

- When the switch is opened (off state), the diode is forward biased. The voltage across the inductor is \( V_L = -V_{OUT} \) (neglecting diode drop). Current \( I_L \) decreases.

1.1 Aim of the thesis work

To enable the measurement of the inductor current and generate a suitable signal conditioning it is suggested that a small electronic board is constructed. The interface will consist of a capacitor, a resistor and operational amplifiers. The capacitor and the resistor are connected in parallel across the converter inductor. It can be shown that the capacitance voltage is proportional to the inductor current.

The aim can be a small electronic board is constructed as a measurement interface between the BMR 450. We are measuring inductor current in the circuit and find proportional relation between inductor current and capacitor voltage.
1.2 Thesis outline

We have total of seven chapters followed by list of figures, list of tables, glossary, appendix and references. In the first chapter there is brief introduction about the DC/DC converters and about Ericsson’s activity in this field. In the second chapter we study different current sensing techniques, and derive relation for inductor current and capacitor voltage, in the third chapter we study the Ericsson 3E Evaluation kit and in fourth chapter we deal with design of the circuit with resistor, capacitor and operational amplifiers, in fifth chapter we perform experimental setup in the laboration and do different experiments in lab. In the sixth chapter we focus on PCB Layouts and companies which are printing PCB, in seventh chapter we end up with conclusion and after there comes Appendix A, B and finally the references.
Chapter 2

Current measurement methods for DC/DC converters

Current sensing is one of the most important functions on a smart power chip. Conventional current-sensing methods insert a resistor in the path of the current to be sensed. This method incurs significant power losses, especially when the current to be sensed is high. This paper presents different current sensing methods. Regardless of the type of feedback control, almost all DC-DC converters and linear regulators sense the inductor current for over-current (over-load) protection. Since instantaneous changes in the input voltage are immediately reflected in the inductor current, current-mode control provides excellent response.

2.1 Series-Sense resistor

This technique is the conventional way of sensing current. It simply inserts a sense resistor in series with the inductor. If the value of the resistor is known, the current flowing through the inductor is determined by sensing the voltage across it. The circuit diagram is shown in Figure 2.1

![Series-Sense resistor diagram]

Figure 2.1 Series-Sense resistor [3].

This method obviously incurs a power loss in $R_{sense}$, and therefore reduces the efficiency of DC-DC converter. For accuracy, the voltage across the sense resistor should be roughly more than 100mV range at full-load because of input-inferred offsets and other practical limitations. In lower output voltages, the percentage of power lost in the sense resistor increases, which degrades efficiency further.
2.2 $R_{DS}$ Sensing

MOSFETs act as resistors when they are ‘ON’ and they are biased in the ohmic (non-saturated) region. Assuming small drain-source voltages, as is the case for MOSFETs when use as switches, the equivalent resistance of the device is as shown in equation (2.2)

$$R_{DS} = \frac{L}{W\mu C_{ox}(V_{GS}-V_T)} \quad [3]$$

Where $W$ is the width of the gate (cm).
$L$ is the Length of the gate (cm).
$\mu$ is the mobility ($cm^2/V * sec$).
$C_{ox}$ is the oxide capacitance per unit area ($F/cm^2$).
$V_T$ is the threshold voltage (Volts).

The circuit diagram is shown in Figure 2.2

Consequently, the switch current is determined by sensing the voltage across the drain-source of MOSFET provided that $R_{DS}$ of the MOSFET is known. The main drawback of this technique is low accuracy. The $R_{DS}$ of the MOSFET is inherently nonlinear. Additionally, the $R_{DS}$ has significant process variation because of $\mu C_{ox}$ and $V_T$, not to mention how it varies across temperature, which can yield a total variance of -50% to 100%.
2.3 Sensor less (observer) approach

This method uses the inductor voltage to measure the inductor current. Since the voltage-current relation of the inductor is \( v = L \frac{di}{dt} \), the inductor current can be calculated by integrating the voltage over time. The value of \( L \) also must be known for this method. When \( R_L \) exists in Figure 2.3 then there is decrease in current and so the accuracy remains the same because accuracy of a measurement system is the degree of closeness of measurements of a quantity to its actual (true) value. The circuit diagram is as shown in Figure 2.3.

![Figure 2.3 Observer current sensing technique [3].](image)

2.4 Average current

This current-sensing technique uses an RC low-pass filter at the junction of the switches of the converter. Since the average current through resistor \( R \) is zero, the output averaged-current is derived as shown in equation (2.4)

\[
I_0 = I_L = \frac{V_{out} - V_{cf}}{R_L} \tag{2.4}
\]

Where \( V_{cf} \) is the average capacitor voltage.

The circuit diagram is as shown in Figure 2.4

The voltage across inductor has a large signal component in addition to current information as the inductor left side is switched between \( V_{IN} \) and ground. Single pole RC (is just a single R and single C, wired in series) filtering is used to control errors. The signal level for IC amplifier estimates the pole frequency. The bandwidth should not be too low as the signal will not be useful for loop control or current limiting. Similar to the MOSFET sensing there is no additional power loss.
If $R_L$ is known, which is not the case for IC designers, the output current can be determined. Sensing the current in this method depends only on $R_L$, and not on the parasitic switch resistor or the values of $R$ and $C$. This scheme is used mainly for load sharing in multiphase DC-DC converters.

2.5 Relation of proportionality for inductor current and capacitor voltage

The block diagram for filtering the voltage across inductor to sense the current is as shown in Figure 2.5

This circuit uses a simple low-pass RC network to filter the voltage across the inductor and sense the current through the inductor [3].

![Figure 2.4 Average current sensing technique [3].](image1)

![Figure 2.5 filtering the voltage across inductor to sense the current [3].](image2)
Using Laplace transform, the voltage across the inductor is

\[ V_L = (R_L + sL)I_L \]  \hspace{1cm} (2.5.1)

Where \( L \) is the inductor, \( R_L \) is resistor through inductor and \( I_L \) is the inductor current. The impedance across the RC branch is

\[ Z = R_c + \frac{1}{sC} \]  \hspace{1cm} (2.5.2)

\[ Z = \frac{1 + sC R_c}{sC} \]  \hspace{1cm} (2.5.3)

The current in the RC branch is equal to the ratio of the inductor voltage to the impedance of the RC branch

\[ I_c = \frac{V_L}{Z} \]  \hspace{1cm} (2.5.4)

Substituting the value of \( Z \) from equation (2.5.3) in equation (2.5.4) we get the equation

\[ I_c = \frac{V_L sC}{1 + sC R_c} \]  \hspace{1cm} (2.5.5)

Applying Kirchhoff voltage law for the RC branch i.e. sum of all the voltages is equal to zero we get equation

\[ V_L = V_c + (I_c R_c) \]  \hspace{1cm} (2.5.6)

Substituting the value of \( I_c \) from equation (2.5.5) in equation (2.5.6) we get the equation

\[ V_L = V_c + \left( \frac{V_L sC}{1 + sC R_c} \right) R_c \]  \hspace{1cm} (2.5.7)

\[ V_c = \frac{V_L}{1 + sC R_c} \]  \hspace{1cm} (2.5.8)

Substituting the value of \( V_L \) from equation (2.5.1) in equation (2.5.8) we get the equation

\[ V_c = \frac{(R_L + sL)I_L}{1 + sC R_c} \]  \hspace{1cm} (2.5.9)

\[ V_c = \frac{R_L \left( 1 + s \left( \frac{L}{R_L} \right) \right) I_L}{1 + sC R_c} \]  \hspace{1cm} (2.5.10)
\[ V_C = R_L \left( \frac{1+sT}{1+sT_1} \right) I_L \]  \hspace{1cm} (2.5.11)

Where \( T = \frac{L}{R_L}, T_1 = C R_C \)

\( T \) is time constant of \( R_L L \) circuit where \( L \) is the inductor and \( R_L \) is the resistor through inductor.

In order to get the voltage across the capacitor proportional to the current in the inductor, the time constants in \( C R_C \) circuit and \( R_L L \) circuit should be equal.

Implies \( T = T_1 \) Then \( V_C = I_L R_L \) \hspace{1cm} (2.5.12)

Hence \( V_C \) would be directly proportional to \( I_L \) [3].
Chapter 3

Ericsson 3E Evaluation kit

3.1 Introduction

The 3E Evaluation Kit has been developed to present a number of benefits and opportunities that come from using digital control and management in power devices. The control and monitoring of a device using a digital communications interface is only one of the many possibilities this technology will provide.

This kit provides everything needed to explore and experiment with the features of Ericsson’s solutions for digital POL (Point of Load power supplies solve the challenge of high peak current demands and low noise margins, required by high-performance semiconductors such as microcontrollers or ASICs, by placing individual power supply regulators (liner or DC-DC) close to their point of use) regulators. When everything is up and running it will be possible to experience how easily parameters can be updated and implemented, virtually instantly, into a POL regulator or an Intermediate Bus Converter (IBC). It will be shown how a network of Point-of-Load devices can be adapted to suit the specific needs of logic devices, from sequencing on start-up to dynamic response, current limiting, sleep modes and more.

3.2 3E Evaluation kit content

The 3E Evaluation kit contains the following items.

- 3E Evaluation board.
- USB cable.
- 20A POL regulator.
- BMR450 data sheet.
- 3E Evaluation kit cd.

We need a computer connected via USB.

3.3 Hardware requirements

The following hardware is not included in the 3E Evaluation kit:

- AC/DC adapter or external power supply.
- Electronic or resistive load capable of handling 0 VDC -12 VDC and up to 50 A of current.

To verify the configurations done via the 3E CMM tool the following additional tools may be required:

- Oscilloscope
- Multimeter
3.4 Hardware assembly

3.4.1 Insert POL regulator

The POL regulator shall be inserted in one of the six available positions on the evaluation board. Use care when inserting the pins of the regulator into the sockets on the board to avoid bending them. When the pins are aligned with the sockets, push gently on the ends of the device and ensure that the device is properly seated. It can be shown in Figure 3.4.1.

![Figure 3.4.1 Insertion of the POL Regulator on the 3E-Evaluation Board [15].](image)

3.4.2 Connect the USB cable

Connection between the evaluation board and your computer is via a USB cable. Insert the mini USB connector in the USB adapter on the board and the standard USB connector to a USB port on your computer. It can be shown in Figure 3.4.2.
3.4.3 Connect the power supply

Power may be provided either via AC/DC adapter connector J1, or from an external power supply to cable attachments on the evaluation board. An AC/DC adapter of 3 V – 14 V DC may be used with the AC/DC adapter connector if the maximum current is not more than 2A. Otherwise, a 3 V - 14 V power supply shall be used and connected to the VCC and GND cable attachments. If you are evaluating a 3E DC/DC converter or Intermediate Bus Converter, a 36 - 75 VDC supply should be attached to the +IN and –IN cable connectors. It can be shown in Figure 3.4.3.
3.4.4 Power up the Evaluation Kit

The POL regulators are preconfigured with Ericsson factory default settings. As soon as power is provided to the board, the POL regulators will power up and provide an output voltage.

3.5 Hardware application

3.5.1 Introduction

The 3E Evaluation Kit contains 2 major hardware assemblies, the 3E evaluation board and the POL regulator.

Below is an overview of the system architecture. The general set-up includes a computer communicating via USB with the PMBus adapter located on the test board. The PMBus adapter translates from the USB to PMBus protocol required for communication with the POL regulator located on the test board. The system architecture is as shown in Figure 3.5.1.

![System architecture](image)

Figure 3.5.1 System architecture [15].

3.6 Evaluation board

The evaluation board is a platform for the user to test PMBus compliant digital POL Regulators. The evaluation board provides the following capabilities.

3.6.1 Evaluation power board

Three ways to power up the board may be used.

- Supply 3V-14V DC to J1 if using an AC/DC adapter.
- Supply 3V-14V DC from an external power supply to VCC and GND if you do not have DC/DC converters installed on the evaluation board.
- Supply 36V-75V DC to IN+ and IN- if you have DC/DC converters installed on the evaluation board.
3.6.2 POL regulators and DC/DC converters

- There are six positions for POL regulators and two positions for DC/DC converters.
- Each POL regulator position supports three footprints (10A, 20A, 40A).

3.6.3 Connections to the test board

Input and output connections of the evaluation board are explained in the Figure 3.6.3.

![Figure 3.6.3 Connections to the test board [15].](image)

The power connections to the test board are shown in Table 3.6.3.

<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>Description</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+IN , -IN</td>
<td>Power input connector (36V-75V DC), max 40A.</td>
<td>Used with DC/DC converters installed on the board</td>
</tr>
<tr>
<td>2</td>
<td>J1</td>
<td>Power input connector (3V-14V DC), max 2A.</td>
<td>Connector to attach AC/DC adapter</td>
</tr>
</tbody>
</table>
3.6.3 Power connections to the test board [15].

### Table 3.6.3 Power connections to the test board

<table>
<thead>
<tr>
<th>3</th>
<th>VCC</th>
<th>Power input connector (3V-14V DC), max 66A.</th>
<th>GND</th>
</tr>
</thead>
</table>

Used with an external power supply when there are no DC/DC converters on the board.

3.6.4 POL regulator positions

There are six identical positions for POL regulators available on the evaluation board. Each position is designed with the following features and possibilities.

- 10A, 20A and 40A footprints are supported by all six positions.
- Addresses are set and printed on each position.

In the Figure 3.6.4 you can find details about the components and their functionality within the POL regulator section of the evaluation board.

![Figure 3.6.4 POL Regulator positions](image)

The 3E Evaluation board hardware components are shown in Table 3.6.4.
<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>J13, J23, J33, J43, J53, J63</td>
<td>CTRL jumper (PMBus/Local)</td>
</tr>
<tr>
<td>2</td>
<td>J12, J22, J32, J42, J52, J62</td>
<td>Jumper to set Vout (1.2V, 1.5V, 1.8V, 3.3V)</td>
</tr>
<tr>
<td>3</td>
<td>J11, J21, J31, J41, J51, J61</td>
<td>Jumper Sync/Vadj</td>
</tr>
<tr>
<td>4</td>
<td>J3, J4</td>
<td>Socket for removable output capacitors (Only in POL SET 3 and 6)</td>
</tr>
<tr>
<td>5</td>
<td>Sw10, Sw20, Sw30, Sw40, Sw50, Sw60</td>
<td>Local CTRL ON/OFF switch</td>
</tr>
<tr>
<td>6</td>
<td>J10, J20, J30, J40, J50, J60</td>
<td>Jumpers for Sense pins</td>
</tr>
<tr>
<td>7</td>
<td>Device address</td>
<td>Device addresses fixed using resistor on test board.</td>
</tr>
</tbody>
</table>

Table 3.6.4  3E Evaluation board hardware components [15].

3.7 POL regulator samples

The following 20A POL regulator is supplied with your kit for use with the evaluation board. Detailed information about performance and specifications can be found in the Technical Specification included on the Evaluation Kit CD. The BMR450 for 20A POL regulator is as shown in Figure 3.7.
3.7.1 Technical specifications

- Small package.
- Size (LxWxH) 25.65 x 12.9 x 8.2 mm (1.01 x 0.51 x 0.323 in.).
- 20 A output current.
- 4.5 V - 14 V input voltage range.
- 0.6 V - 5.5 V output voltage range (by PMBus).
- 0.7 V – 5 V output voltage range (by external resistor).
- High efficiency, typ. 96.8 % at half load, 5 Vin, 3.3 Vout.
- 5 million hours MTBF.
- Through hole and surface mount versions.
- PMBus read and write compliant.

3.7.2 General characteristics

- Voltage/current/temperature monitoring.
- Precision delay and ramp-up.
- Voltage sequencing.
- Switching frequency synchronization.
- Configurable control loop.
- Non-linear transient response.
- Wide output voltage adjust function.
- Start up into a pre-biased output safe.
- Output short-circuit protection.
- Over temperature protection.
- On/Off inhibit control.
- Output voltage sense.
- ISO 9001/14001 certified supplier.
Chapter 4

Design of measurement circuit with resistor, capacitor values and operational amplifiers

To enable the measurement of the inductor current and generate a suitable signal conditioning it is suggested that a small electronic board is constructed. The interface will consist of a capacitor, a resistor and operational amplifiers. As mentioned in chapter 1, the capacitor and the resistor are connected in series and are connected in parallel across the converter inductor. It can be shown that the capacitance voltage is proportional to the inductor current, it is shown in section 2.5.

4.1 Description of the circuit

From Figure 4.3 the circuit is described as follows:

T is the switching transistor which is controlled by a pulse width modulated signal about 300 kHz. I is the total current flow in the circuit.

$I_L$ is the current flowing into the BMR450 inductor.

$I_C$ is the current flowing into the designed circuit capacitor.

$R_L$ is the resistance through inductor.

L is the power train inductance in the BMR450.

$R_C$ is the resistor in the measurement circuit.

C is the capacor in the measurement circuit for the designed circuit.

The values for the BMR450 power train inductor are:

- $R_L$ approximative $= 2\, \text{m}\Omega$
- $L = 0.9\, \mu\text{H}$

These values are the standard values of BMR450 power train inductor [18].

4.2 Design of the measurement circuit

Refer to an equation in section 2.5 we get the equation

$$T = \frac{L}{R_L} = R_C \cdot C \quad (4.2.1)$$

Substituting the values of L and $R_L$ in the equation (4.2.1) we get the equation

$$T = \frac{9 \cdot 10^{-7}}{2 \cdot 10^{-3}} = 4.5 \cdot 10^{-4} \quad (4.2.2)$$

Equating the equations (4.2.2) and (4.2.1) we get the equation
\[ R_cC = 4.5 \cdot 10^{-4} \]  \hspace{1cm} (4.2.3)

Therefore \( R_c = \frac{4.5 \cdot 10^{-4}}{C} \)  \hspace{1cm} (4.2.4)

If we choose capacitor value as 0.1\(\mu\)F then we can calculate the value of \( R_c \) by substituting the value of \( C \) in equation (4.2.4) as follows:

\[ R_c = \frac{4.5 \cdot 10^{-4}}{0.1 \cdot 10^{-6}} = 4.5k\Omega, \]  but we take \( R_c \) value as 5k\(\Omega\) in practical due to the tolerance present in the resistor.

4.3 Design of the circuit including operational amplifiers

4.4 Load resistor

We are calculating the load resistor value as follows:

From ohms law

\[ V_{OUT} = I_{avg}R_{Load} \]  \hspace{1cm} (4.4.1)

\[ R_{Load} = \frac{V_{OUT}}{I_{avg}} \]  \hspace{1cm} (4.4.2)

Figure 4.3 Designed RC circuit including operational amplifier [3].
Since we have chosen to perform our experiments at 5.0 volt and current ranges from 2<I < 20A.

So for different values of current we get different load resistor values and we plan to perform experiments for the values in the Table 4.4.

<table>
<thead>
<tr>
<th>Average current</th>
<th>Load Resistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>I = 0 A</td>
<td>No Load</td>
</tr>
<tr>
<td>I = 3.4 A</td>
<td>R = 1.47Ω</td>
</tr>
<tr>
<td>I = 6.2A</td>
<td>R = 0.80 Ω</td>
</tr>
<tr>
<td>I = 8.4 A</td>
<td>R = 0.59 Ω</td>
</tr>
</tbody>
</table>

Table 4.4 Load resistors for different current values.

4.5 Voltage follower

This can be implemented using IC741. The main purpose of voltage follower is:

1) To acquire very high input impedance.
2) To make our circuit resistant to slight variations in the system.

The circuit diagram for voltage follower is as shown in Figure 4.5.1.

![Voltage Follower Circuit Diagram](image)

Figure 4.5.1 Voltage Follower [16].

The pin diagram for the voltage follower is as shown in Figure 4.5.2.
4.6 Instrumentational amplifier

1) The main purpose of using instrumentational amplifier is to get very high input impedance and a single ended output.
2) These are the high gain differential amplifiers.
3) They have very good common mode rejection ratio (CMRR).

CMRR – It is the measure of tendency of device to reject input signals common to both input leads. A high CMRR is important in applications where signal of interest is represented by a small voltage fluctuation superimposed on a possibly large voltage offset.

General instrumentational amplifier circuit is as shown in Figure 4.6.1.
The formula for the output voltage is

\[ V_{\text{out}} = (V_2 - V_1) \left( 1 + \frac{2R_1}{R_{\text{gain}}} \right) \frac{R_3}{R_2} \]  \hspace{1cm} (4.6.1)

Where \( V_{\text{out}} \) - output voltage.

\( V_1 \) & \( V_2 \) - input voltage signals.

\( R_1, R_2 \) & \( R_3 \) - resistances.

\( R_{\text{gain}} \) - gain resistance.

If the gain value is known we can estimate the resistance values and thus we can calculate the output voltage.

Since the above circuit is bulky in size we prefer to use an IC INA111, schematic of which is shown in Figure 4.6.2.
The three advantages of using instrumentational amplifier are:

1) Open-loop gain is boosted for increasing programmed gain, thus reducing gain related errors.
2) The gain-bandwidth product increases with programmed gain, thus optimizing frequency response.
3) The input voltage noise is reduced to a value of 9 nV/√Hz.

The gain equation is

\[ G = \frac{50k\Omega}{R_G} + 1 \]  \[ (4.6.2) \]

Where \( G \) - gain.
\( R_G \) - gain resistance.
Chapter 5

Experimental setup

We are performing experiments in lab for the measurement circuit (designed circuit) i.e. a series RC circuit followed by operational amplifiers in parallel to the BMR450 i.e. series RL circuit. The equipment we require for laboration is:

- Bread board.
- Power supply.
- Function generator.
- Oscilloscope.
- Multimeter.
- Probes and connecting wires.

5.1 Bread Board

A breadboard is used to make up temporary circuits for testing or to attempt an idea and verifying the function. No soldering is required, so it is effortless to change connections and replace components. These parts will not be damaged so that they will be available to use again afterwards. More or less all the electronic projects started life on a breadboard to check that the circuit worked as designed.

The following Figure 5.1 shows a typical small breadboard which is suitable for basic structure simple circuits with one or two ICs (chips).

Figure 5.1 Bread Board [22].
Breadboards have many small sockets (called ‘holes’) arranged on a 0.1 grid. The leads of most components can be pressed straight in to the holes. ICs are inserted across the central gap with their notch or dot to the left.

Wire links can be made with single-core plastic-coated wire of 0.6mm diameter (the standard size). Stranded wire (A metal wire that is made up of several smaller wires twisted together. Stranded wire is more flexible than wire with a solid core) is not suitable because it will crush when pushed into a hole and it may damage the board.

5.2 Electrical Connections and applied voltages

We are connecting the series RC circuit in parallel to the BMR450. One end of the BMR450 circuit i.e., inductor is connected to the capacitor and other end i.e., resistor through inductor is connected to the resistor through capacitor.

We are connecting 5kΩ resistor in series with 0.1µF capacitor on breadboard with input voltage of 12v across measurement circuit ($V_{IN}$ in Figure 4.3) and measuring output across capacitor with probes connected to the oscilloscope and the capacitor. Connecting the oscilloscope across the capacitor and positive pin to the capacitor one end and negative pin to the capacitor other end the output observed is a triangle wave.

The output voltage across the capacitor is given as input to the op-amp pin 2 (refer Figure 4.6.2) and supply voltage of +15 Vcc is given to the pin 7 and supply voltage of -15 Vcc is given to pin 4 and resistor $R_G$ is connected between the pins1 and 8. Pin 3 is connected to the capacitor positive end. The output is taken across pin 6.

Since the output voltage for the measurement circuit should be between 5-10V so the gain can be chosen according to the output voltage across capacitor. Here gain in electronics/amplifier can be chosen as 10.88, accordingly we can calculate the value of $R_G$ as below:

Refer to equation 4.6.2 we can calculate the value of $R_G$ as

$$R_G = \frac{50k\Omega}{G - 1} \quad [19]$$

$$R_G = \frac{50k\Omega}{9.88} = 5k\Omega$$

5.3 Measuring current

Voltage can be measured directly by using multimeter across the load resistor by keeping positive pin in multimeter to the red and negative pin to the ground where as we cannot measure current directly.
Current can be measured by keeping load resistor in series with the multimeter, i.e. load resistor positive terminal is connected to the negative pin of the multimeter and multimeter positive pin is connected to the red pin in the 3E-Evaluation board and black pin is connected to the load resistor other terminal.

5.4 Measurement voltage across the measurement capacitor C

With reference to the Figure 4.3 when we connect the capacitor terminals to the oscilloscope when there is no load resistor, we get measurement voltage across the measurement capacitor C, the plot for which is shown in Figure 5.4.

![Graph of measurement voltage across the measurement capacitor C](image)

Figure 5.4 Measurement voltage across the measurement capacitor without load resistor with disturbances.

We can calculate the frequency, \( f \), from the Figure 5.4 if we know the value of period time, \( T \), and the time period for one complete cycle from the Figure 5.4 is 2.55\( \mu \)Sec so the frequency is given by

\[
f = \frac{1}{T} = \frac{1}{2.55 \cdot 10^{-6}} = 392.15 kHz\]

(5.4.1)
Average current should be same in the inductor as in the load and is not same in instant current. Since we know that output voltage is 5V and there is no load resistor, average current can be calculated as

$$I_{avg} = \frac{V}{R}$$  \hspace{1cm} (5.4.2)

Since there is no load resistor the average current in this case will 0. Using mat lab we can calculate the average voltage and it can be 0.00035V. The corresponding average current is calculated in section 5.6.

### 5.5 Output across instrumentation amplifier INA111

With reference to the Figure 4.3 when we connect the INA111 amplifier pin 6 (refer Figure 4.6.2) to the oscilloscope when there is without load resistor, we get output across instrumentation amplifier, which also can be estimated to zero, the plot for which is shown in Figure 5.5.

![Figure 5.5 Output across INA111 amplifier without load resistor.](image-url)
5.6 Output across capacitor in terms of inductor current

Without load resistor, the current flowing through inductor as measured as voltage can be calculated as follows:

From section 2.5, equation (2.5.12) we know proportionality relation for capacitor voltage in terms of inductor current as

\[ V_C = I_L R_L \]

Where \( V_C \) - Voltage across capacitor.

\( I_L \) - Current through inductor.

\( R_L \) - Resistor through inductor.

We assume the value of \( R_L = 2 \text{m} \Omega \)

By removing disturbances in the Figure 5.4, measurement voltage across measurement capacitor without load resistor without disturbances can be shown in Figure 5.6.1.

![Figure 5.6.1](image.png)

**Figure 5.6.1** Measurement voltage across measurement capacitor without load resistor without disturbances.

The average value of the current for the whole measurement vector can be calculated by calculating the average voltage using MATLAB (is a tool for numerical computation and visualization) and the value is 0.00035V for full number of periods and substituting this value in the equation 2.5.12
\[ I_L = \frac{0.00035}{2 \cdot 10^{-3}} \]

\[ I_L = 0.17 \text{ A} \]

Figure 5.6.2 Output across capacitor without load resistor in terms of inductor current.

The same experiment is performed for different loads and also when there is mismatch between the time constant in the measurement circuit and the inductor and results obtained are shown in section 5.7.

5.7 For different load resistors, measurement voltage across the measurement capacitor \( C \) and instrumentation amplifier

When Load resistor =1.47\( \Omega \) we observe measurement voltage across the measurement capacitor \( C \), across instrumentation amplifier INA111.

The plot for measurement voltage across the measurement capacitor with disturbances is shown in Figure 5.7.1.
Figure 5.7.1 Measurement voltage across the measurement capacitor when load resistor = 1.47Ω with disturbances.

Measurement voltage across the measurement capacitor C

With reference to the Figure 4.3 when we connect the capacitor terminals to the oscilloscope with load resistor = 1.47Ω we get measurement voltage across the measurement capacitor, the plot for which is shown in Figure 5.7.2.

Refer to equation 5.4.2 we calculate average current when there is load resistor of 1.47Ω as

\[
I_{avg} = \frac{5}{1.47\Omega}
\]

\[
I_{avg} = 3.40A
\]

For 1.47Ω load resistor the average current will be 3.40A.
Figure 5.7.2 Measurement voltage across the measurement capacitor when load resistor = 1.47Ω without disturbances.

The average value of the current for the whole measurement vector can be calculated by calculating the average voltage using mat lab and the value is 0.0096V and substituting this value in the equation 2.5.12

\[ I_L = \frac{0.0096}{2 \cdot 10^{-3}} \]

\[ I_L = 4.8 \text{A} \]

Disturbances are larger when there is current because when the switch is opened due to inductance in the line there give large disturbances in the voltage.

Output across INA111:

The plot for output across instrumentation amplifier when load resistor = 1.47 Ω is shown in Figure 5.7.3.
When load resistor =0.80Ω we observe measurement voltage across the measurement capacitor, across instrumentation amplifier INA111.

The measurement voltage across the measurement capacitor with disturbances can be shown in Figure 5.7.4.

Figure 5.7.3 Output across instrumentation amplifier INA111 when load resistor =1.47Ω.

Figure 5.7.4 Measurement voltage across the measurement capacitor when load resistor = 0.80Ω with disturbances.
The noise or disturbances are filtered by cutting noise portions in the Figure 5.7.4 for all the periods.

**Measurement voltage across the measurement capacitor C**

With reference to the Figure 4.3 when we connect the capacitor terminals to the oscilloscope with load resistor = 0.80 Ω we get measurement voltage across the measurement capacitor, the plot for which is shown in Figure 5.7.5.

![Figure 5.7.5 Measurement voltage across the measurement capacitor when load resistor = 0.80Ω without disturbances.](image)

Refer to equation 5.4.2 we calculate average current when there is load resistor of 0.80Ω as

\[
I_{\text{avg}} = \frac{5}{0.80}
\]

\[
I_{\text{avg}} = 6.25\text{A}
\]

For 0.80Ω load resistor the average current will be 6.25A.

The average value of the current for the whole measurement vector can be calculated by calculating the average voltage using mat lab and the value is 0.0152V and substituting this value in the equation 2.5.12
\[ I_L = \frac{0.0152}{2 \cdot 10^{-3}} \]

\[ I_L = 7.6 \text{A} \]

When load resistor = 0.59\(\Omega\) we observe measurement voltage across the measurement capacitor, across instrumentation amplifier INA111.

The measurement voltage across the measurement capacitor with disturbances can be shown in Figure 5.7.6.

![Output across capacitor when load resistor=0.59 ohm](image)

Figure 5.7.6 Measurement voltage across the measurement capacitor when load resistor = 0.59\(\Omega\) with disturbances.

Measurement voltage across the measurement capacitor C

With reference to the Figure 4.3 when we connect the capacitor terminals to the oscilloscope with load resistor = 0.59 \(\Omega\) we get measurement voltage across the measurement capacitor, the plot for which is shown in Figure 5.7.7.
Refer to equation 5.4.2 we calculate average current when there is load resistor of 0.59Ω as

\[
I_{avg} = \frac{5}{0.59}
\]

\[
I_{avg} = 8.47\text{A}
\]

For 0.59Ω load resistor the average current will be 8.47A.

The average value of the current for the whole measurement vector can be calculated by calculating the average voltage using mat lab and the value is 0.0217V and substituting this value in the equation 2.5.12

\[
I_L = \frac{0.0217}{2 \cdot 10^{-3}}
\]

\[
I_L = 10.85\text{A}
\]
Output across INA111:

The plot for output across instrumentation amplifier INA111 when load resistor = 0.59Ω is shown in Figure 5.7.8.

The peak-peak voltage across capacitor can be estimated to be 0.05V (refer Figure 5.7.6) and the gain in the electronics/amplifier can be estimated to be 10.88 (refer Section 5.2) then the peak-peak voltage across amplifier in this case should be 0.544V and from the Figure 5.7.8 the peak-peak voltage across INA111 amplifier can be estimated to be 0.5V which is close to the general case.

From the above results we observe the average current in the inductor and in the load should be same and if we find relative error for different loads it can be as follows: when we have a load resistor of 1.47Ω then the relative error in this case is 0.41, when load resistor is 0.80Ω then the relative error is 0.21, when load resistor is 0.59Ω then the relative error is 0.280.
5.8 Mismatch between time constants

When there is mismatch between the time constant in the measurement circuit and the inductor we plot the graph for output across capacitor and results obtained are shown in Figure 5.8.1.

When $R_C=9\text{k}\Omega$, Load resistor $=0.3\Omega$ we observe measurement voltage across the measurement capacitor.

Measurement voltage across the measurement capacitor $C$

In the above manner if we connect connections on breadboard and observer wave form for measurement voltage across the measurement capacitor when load resistor $=0.3\Omega$ and time constants (product of $R_C C$ and $\frac{L}{R_L}$) are not same i.e. $R_C=9\text{k}\Omega$, $R_C C$ is larger than the proper one and it is expected to change the triangle shape to the expected shape as shown in Figure 5.8.1.

![Output across capacitor when $R_C=9\text{k}\Omega$, load resistor $=0.3\Omega$.](image)

Figure 5.8.1 Measurement voltage across the measurement capacitor when $R_C=9\text{k}\Omega$, load resistor $=0.3\Omega$. 
Chapter 6

PCB Layout:

In this chapter we deal with the layouts and the companies that use the layout to print PCB (Printed Circuit Board) for the circuit which we designed and tested in lab. After designing the circuit we perform several experiments in lab and there after we are drawing a schematic figure for the same circuit so that if we give that schematic circuit for printing to get that circuit to be printed on PCB. The suggested PCB layout is as shown in Figure 6.0.

Figure 6.0 PCB layout.

Where R1 = R_C.

\[ C_1 = C. \]

\[ R_2 = R_G \text{ (Gain resistance in the amplifier).} \]

U1 - voltage follower (IC741).

U2 – Instrumentation amplifier (INA111).

J1 – supply line.

We have contacted companies for printing PCB among that first company is Smart Search Solutions [23] which was started in 2009 with a goal to serve global clients in various fields. They provide quality of service to the clients and their smart work helps us in gaining faith from the clients. Smart search with in a very less time proved its determination and attained projects from the giants of the industry. They provide service in various domains like Auto Card
Digitization, Embedded systems; web designing, printing PCB for the designed circuits. They charge for the PCB based on the size of the circuit and are going to deliver the product within 2 weeks.

The second company is Pentagon Embedded Solutions [24] which was started in 2010, is an advanced technology company from India covering the full spectrum of technology services. They are specialized in end to end services. Their service spectrum covers application development, application maintenance, hardware development, firmware development, embedded systems and services. They focus on strong customer relationship and delivery ownership. Customer satisfaction is main motto. Rich technological capabilities and industry exposure enables them to reach beyond the basic IT Services to design and deliver projects, products and implement end to end solutions to customers in variety of industries. They are going to print PCB based on size, no of layers, on thickness and also on the complexity of the components and are going to deliver the product within 1-4 weeks.

The other company is Daletech Electronics Ltd [25] was established in 1987, is a leading provider of contract electronic manufacturing services (CEM), PCB assembly, electronic assembly, electronic design and regulatory compliance services. We face the challenge of reducing costs and time to market while producing products that incorporate the latest electronic technology, meet complex regulatory requirements and involve sophisticated electronic manufacturing processes. Daletech Electronics gives us access to the latest electronic product design and contract electronic manufacturing CEM, PCB assembly services as well as technical and regulatory knowledge without the need for significant capital investment. To design a PCB based on our schematic and produce a sample assembled will total cost of £500 and it will be delivered in 3-4 weeks.
Chapter 7

Conclusion

In this thesis work we constructed a measurement circuit for measurement of the inductor current in the buck converter BMR450. We theoretically show that the voltage across the capacitor is directly proportional to the inductor current in the BMR450. We designed a test bed to enable the measurement of the inductor current. On the base of the measurement signal we derived the average inductor current for different resistive loads. We draw schematic PCB layout for the measurement circuit.

During the project we observed that the measurement electronics has to be chosen for relatively high bandwidth, about 2MHz. We also observed that the measurement signal has a large noise magnitude, induced by the transistor switchings. The noise magnitude directly after the switchings is so high that the part of the measurement signal was not used in the further calculations. The relative error in the derivation of the average inductor current was about 20% at 50% load and about 40% at 20% load.
Appendix A - Software installation

A.1 Driver installation

Hardware device drivers are included in the CD-ROM. Follow the steps below to install device drivers.

Connect the USB cable to USB port in the computer and on the Evaluation board. A message is shown “Found New hardware”.

An installation wizard will start

Choose the option “Search for the suitable driver for my device” click “Next”
Select “Specify a location” click “Next”

Click “Browse” and choose “\<CD-ROM Drive>\drivers\ftd2xx.inf”
Click “Next”

Click “Finish”
Completing the Found New Hardware Wizard

Ziker Labs PMBus Interface

Windows has finished installing the software for this device.

To close this wizard, click Finish.
Appendix-B

Computer system requirements

The minimum computer system requirements are:

- Intel Pentium III or compatible 500 MHz or higher processor.
- 128MB of RAM.
- 300 MB (x86), 630 MB (x64) of available hard-disk space to install the 3E CMM tool software.
- USB 1.0 port or higher.
- 1,024x768 monitor resolution with 16-bit or greater video card.
- CD-ROM or DVD driver (required for compact disc installation).

Software requirements

Supported Operating System:
Windows 2000 Service Pack 4*.

The following software is required:

- Windows Installer 3.0. Windows Installer 3.1 or later is recommended.
- IE 5.01 or later:

Other features

- On board USB to PMBus adapter.
- Control switch (CTRL ON or OFF).
- Preset addresses for all six POL regulator positions.
- Vout jumpers for the POL regulators BMR 45x 00/02 and BMR 45x 00/03 (user can set 1.2V, 1.5V, 1.8V, 3.3V via jumper).
- Position for removable output capacitors (on address x12 and x20).
References


[18] Project in the course Adaptive filtering, ET2415, BTH, spring 2009, Anders Hultgren, “Table of Data for Ericsson’s BMR 450”.


