DEVELOPMENT OF A DOUBLE-INPUT INTERLEAVED BOOST DC-DC CONVERTER

YONIS. M. YONIS BUSWIG

UNIVERSITI TUN HUSSEIN ONN MALAYSIA
DEVELOPMENT OF A DOUBLE-INPUT INTERLEAVED
BOOST DC-DC CONVERTER

YONIS. M. YONIS BUSWIG

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2016
For my beloved mother and father.

Thank you for your prayer for me whole this time.

I love you very much.
Acknowledgment

"Alhamdulillah", all praise to ALLAH, the most gracious and the most merciful, for all the strength and will provided to the author in completing the research. Without "the mercy", the author is just an ordinary person who may not even understand what the research topic is all about.

The author would like to express utmost appreciation and gratitude to the research supervisor, Dr Wahyu Mulyo Utomo for his guidance, persistent encouragement and associated aid throughout the research period. His understanding and patience during the tough period are forever appreciated.

Heartiest thanks are due to the senior technician for his full cooperation for the research. Appreciation is also dedicated to those who contributed directly or indirectly towards the success of this thesis.

Finally, sincere thanks are dedicated to the author’s parents and family for their consistent prays, patience and never-ending support. May ALLAH bless all of us.

Last but not least, thank you to all my friends for their helps, criticisms and ideas. Also, to LyX developers all over the world, thank you for this useful document processor that helped me a lot for a nice formatting thesis writing.

Yonis. M. Yonis Buswig
Parit Raja
Abstract

Suitable integration of several energy sources profoundly depends on the power electronic converters which interface multiple energy sources that having different characteristics. Conventionally, multiple sources are connected either in series or parallel configurations. However, these configurations have disadvantages such as having difficulty to achieve regulated output voltage and produce high ripples. Consequently, it is more beneficial to use a multi-input converter rather than several independent converters, as it results in less components, simpler control, more stability, and also lower ripples. In this research, a double-input boost DC-DC converter (DIBC) is proposed using the concept of pulsating voltage source cells (PVSCs) for synthesis and generation of input sources circuit combined with double inductors interleaved concept as ripple reduction technique in order to reduce the current ripple. The proposed double-input converter is composed of two voltage sources that accommodated with converter cell and the conduction of interleaving switches decides the interleaved operating mode and boosting level. Different operating modes of the proposed converter are obtained as well as its corresponding voltage ratios are derived. In the controller design, a Pulse Width Modulation (PWM) technique is used to control the commuting switches while the neural network (NN) control algorithm is used to manage and regulate output voltage of the proposed DIBC. The NN controller is trained by the online back propagation algorithm to achieve output voltage regulation despite variations in line voltage and the load; as well output voltage tracking capability. The proposed DIBC system has been investigated through simulation using the MATLAB/Simulink environment and validated experimentally on a laboratory prototype using DSP TMS320F28335 real-time digital controller. The conducted simulation and experiments obtained good results for low ripples and voltage regulation.
Abstrak

Integrasi yang sesuai untuk beberapa sumber tenaga sangat bergantung kepada kuasa penukar elektronik dimana ia berhubung kait dengan pelbagai sumber tenaga yang mempunyai berbeza ciri-ciri. Konvensional, pelbagai sumber tenaga disambungkan sama ada dalam konfigurasi siri atau selari. Walau bagaimanapun, konfigurasi- konfigurasi ini mempunyai kelemahan seperti mempunyai kesukaran untuk mencapai voltan keluaran yang dikawal selia dan menghasilkan riak-riak tinggi. Oleh itu, adalah lebih bermanfaat dengan menggunakan sebuah penukar pelbagai input daripada beberapa penukar yang tersendiri, kerana ia mempunyai kebaikan dengan mengurangkan komponen, kawalan mudah, lebih stabil, dan menghasilkan riak lebih rendah. Dalam kajian ini, penukar peningkat DC DC dengan dua-input (DIBC) telah dicadangkan dengan menggunakan konsep sumber voltan berdenyut sel-sel (PVSCs) untuk sintesis dan penjanaan litar sumber input dan menggabungkan dengan dua pengaruh yang interleave konsep sebagai teknik pengurangan riak untuk mengurangkan riak arus. Penukar dua input yang dicadangkan terdiri daripada dua sumber voltan yang disesuaikan dengan sel penukar dan konduksi interleaving suis memutuskan mod operasi interleaved dan tahap peningkatan. Mod operasi yang berbeza untuk penukar yang dicadangkan telah diperolehi serta nisbah-nisbah voltan berkenaan. Dalam reka bentuk pengawal, teknik pulse width modulasi (PWM) telah digunakan untuk mengawal suis ulang-alik manakala algoritma kawalan neural network (NN) digunakan untuk mengurus dan mengawal output voltan DIBC yang dicadangkan. Pengawal NN dilatih oleh talian algoritma rambatan balik untuk mencapai peraturan voltan walaupun variasi dalam voltan talian dan beban; serta keupayaan pengesanan voltan keluaran. Sistem DIBC yang dicadangkan ini telah disiasat melalui simulasi dengan menggunakan MATLAB / persekitaran Simulink dan disahkan secara eksperimen dengan prototaip makmal dengan menggunakan DSP TMS320F28335 pengawal digital masa nyata. Simulasi dan eksperimen yang dijalankan mendapat keputusan yang baik dengan riak-riak yang rendah dan voltan peraturan.
# Contents

Declaration ii  
Dedication iii  
Acknowledgment iv  
Abstract v  
Abstrak vi  
List of Figures xi  
List of Tables xx  
List of Appendices xxi  
List of Nomenclatures xxii  

## Chapter 1 Introduction 1  
1.1 Introduction 1  
1.2 Research Background 1  
1.3 Problem Statements 3  
1.4 Research Objective 3  
1.5 Research Scope 4  
1.6 Research Methodology 4  
1.7 Thesis Outline 5  

## Chapter 2 Literature Review 7  
2.1 Introduction 7  
2.2 Overview of Basic DC-DC Converters 7  
  2.2.1 Basic DC Power Converter System 7  
  2.2.2 Basic Circuit of DC-DC Converter 8
Chapter 3  Methodology  38

3.1  Introduction  38

3.2  Configuration of the Proposed Double-input DC-DC Converter  38

3.3  Circuit of the Proposed Double-input Boost Converter  39
  3.3.1  The Proposed Double-input Circuit  40
  3.3.2  The Proposed LC Filter Circuit  41

3.4  Switching Patterns for Proposed Double-input Boost Converter  42
  3.4.1  Decision of Duty Ratio for Main Switches  42
  3.4.2  Decision of Duty Ratio for Interleaving Switches and Number of Phases  43

3.5  Components Selection of the Proposed Double-input Boost Converter  44
  3.5.1  Design and Selection of Uncoupled Inductors  45
3.5.2 Design and Selection of Output Filter 46

3.6 Operating Principle of the Proposed Double-Input DC-DC Converter 46

3.7 Voltage Transfer Ratio of the Proposed Double-Input DC-DC Converter 51

3.8 Proposed Control of Double-Input DC-DC Converter 53
  3.8.1 Block Diagram of Proposed Control 53
  3.8.2 Design of Proposed Neural Network Control 54
    3.8.2.1 Structure of Proposed Neural Network Controller Algorithm 54
    3.8.2.2 Learning Algorithm of Back propagation 55

3.9 Summary 57

Chapter 4 Research Design and Results 58

4.1 Introduction 58

4.2 Comparative Studies on Conventional Double-input DC-DC Converter 58

4.3 Overview of Proposed System Development 100

4.4 Simulation Model of the Proposed Double-Input Boost Converter 101
  4.4.1 Open-Loop Simulation Model 101
  4.4.2 Open-Loop Simulation Results 103
    4.4.2.1 Matched Input Voltage Sources 103
    4.4.2.2 Mismatched Input Voltage Sources 106
    4.4.2.3 Voltage Regulation Capability 114
  4.4.3 Closed-Loop Simulation Model 118
    4.4.3.1 Closed-Loop Simulation Results 119
    4.4.3.2 Line Regulation Capability 119
    4.4.3.3 Load Regulation Capability 120
    4.4.3.4 Voltage Regulation Capability 121

4.5 Hardware Development and Implementation 129
  4.5.1 Prototype Design of the Proposed Double-Input Circuit 130
  4.5.2 Integration of MATLAB Model with Prototype circuit of Proposed Double-Input Converter 130
  4.5.3 Experimental Set-up of the Double-input Boost Converter Circuit 132
  4.5.4 Experimental Results 132
Chapter 5 Conclusion and Future Work 154

5.1 Conclusion 154
5.2 Future Work 156

References 157

Vitae 191
## List of Figures

<table>
<thead>
<tr>
<th>Figure No</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Block diagram of a DC power converter system (Liu &amp; Lee, 1988).</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Basic DC–DC converter topologies (Liu &amp; Lee, 1988).</td>
<td>9</td>
</tr>
<tr>
<td>2.3</td>
<td>Typical inductor current waveform of the DC-DC converters (Mitchell, 1988).</td>
<td>11</td>
</tr>
<tr>
<td>2.4</td>
<td>Equivalent circuit of voltage mode control (Liu &amp; Lee, 1988).</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>Parallel-connected converter (Camara et al., 2006).</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>Series-connected converters (Camara et al., 2006).</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>Photovoltaic system using a multi-input converter (Camara et al., 2006).</td>
<td>17</td>
</tr>
<tr>
<td>2.8</td>
<td>Multi-input flyback DC-DC converter (Zhao et al., 2008).</td>
<td>18</td>
</tr>
<tr>
<td>2.9</td>
<td>Isolated multi-input boost half-bridge DC-DC converter (Tao et al., 2008b).</td>
<td>19</td>
</tr>
<tr>
<td>2.10</td>
<td>Isolated multi-input boost full-bridge converter (Tao et al., 2008b).</td>
<td>19</td>
</tr>
<tr>
<td>2.11</td>
<td>Isolated multiple-input with two full-bridge DC-DC converter (Chen et al., 2001).</td>
<td>20</td>
</tr>
<tr>
<td>2.12</td>
<td>Isolated multiple-input ZVS bidirectional DC-DC converter (Caricchi et al., 1993).</td>
<td>21</td>
</tr>
<tr>
<td>2.13</td>
<td>High step-up multi-input bidirectional isolated converter (Liu &amp; Li, 2005).</td>
<td>21</td>
</tr>
<tr>
<td>2.14</td>
<td>Multi-input converters derived from H-bridge structure (Ahmadi &amp; Ferdowsi, 2012).</td>
<td>22</td>
</tr>
<tr>
<td>2.15</td>
<td>Multiple input DC-DC converter with battery/ultra-capacitor (Li et al., 2009).</td>
<td>23</td>
</tr>
<tr>
<td>2.16</td>
<td>Multi-Input Z-Source DC-DC converter (Sedaghati &amp; Babaei, 2011).</td>
<td>24</td>
</tr>
</tbody>
</table>
2.17 Multiple-input with four-phase bidirectional flyback converter (Bhattacharya et al., 2009).
2.18 Extendable single-stage multi-input DC–DC/AC boost converter (Danyali et al., 2014).
2.20 Integrated multi-input buck-buckboost converter (Benavides & Chapman, 2005).
2.21 Integrated buckboost-buckboost converter (Yalamanchili et al., 2006).
2.22 Multile-input SEPIC converter (Kwasinski, 2009).
2.23 Multiple-input Cuk converter (Kwasinski, 2009).
2.25 Fuzzy logic control system (So et al., 1996).
2.26 One-cycle control system (Smedley & Cuk, 1995).
2.27 Sliding mode control system (Bilalovic et al., 1983).
2.28 Neural network control system (Chan et al., 1993).
3.1 General block diagram of the proposed double-input DC-DC converter.
3.2 The proposed double-input boost converter circuit.
3.3 The proposed double-input circuit.
3.4 The two interleaved inductors $L_1$ and $L_2$.
3.5 Input current with inductors current operating out of phase.
3.6 Switching pattern of main switches $S_1$ and $S_2$.
3.7 Switching pattern of interleaving switches $S_3$ and $S_4$.
3.8 Circuit diagram of the proposed converter.
3.9 Switching patterns and current waveforms of the proposed converter.
3.10 Operating Mode I at time $t_1$.
3.11 Operating Mode II at time $t_2$.
3.12 Operating Mode III at time $t_3$.
3.13 Operating Mode IV at time $t_4$.
3.14 Block diagram of voltage controller design.
3.15 Architecture of the proposed neural network controller.
4.1 Circuit diagram of double-input boost converter.
4.2 Simulation model circuit of double-input boost converter.
4.3 Total input current waveform.
4.4 Ripple of total input current waveform.
4.5 Output current waveform.  61
4.6 Ripple of output current waveform.  62
4.7 Output voltage waveform.  62
4.8 Ripples of output voltage waveform.  63
4.9 Resulted ripples of output voltage waveforms due to its double-input voltage sources.  63
4.10 Circuit diagram of double-input boost converter.  65
4.11 Simulation model circuit of double-input boost converter.  65
4.12 Total input current waveform.  66
4.13 Ripples of total input current waveform.  66
4.14 Output current waveform.  67
4.15 Ripples of output current waveform.  67
4.16 Output voltage waveform.  68
4.17 Ripples of output voltage waveform.  68
4.18 Resulted ripples of output voltage waveforms due to its double-input voltage sources.  69
4.19 Circuit diagram of double-input buck converter.  70
4.20 Simulation model circuit of double-input buck converter.  71
4.21 Total input current waveform.  72
4.22 Ripples of total input current waveform.  72
4.23 Output current waveform.  73
4.24 Ripples of output current waveform.  73
4.25 Output voltage waveform.  74
4.26 Ripples of output voltage waveform.  74
4.27 Resulted ripples of output voltage waveforms due to its double-input voltage sources.  75
4.28 Circuit diagram of double-input buck converter.  76
4.29 Simulation model circuit of double-input buck converter.  77
4.30 Total input current waveform.  78
4.31 Ripples of total input current waveform.  78
4.32 Output current waveform.  79
4.33 Ripples of output current waveform.  79
4.34 Output voltage waveform.  80
4.35 Ripples of output voltage waveform.  80
4.36 Resulted ripples of output voltage waveforms due to its double-input voltage sources.  81
4.37 Circuit diagram of double-input buck-boost converter.  82
4.38 Simulation model circuit of double-input buck-boost converter.  83
4.39 Total input current waveform. 84
4.40 Ripples of total input current waveform. 84
4.41 Output current waveform. 85
4.42 Ripples of output current waveform. 85
4.43 Output voltage waveform. 86
4.44 Ripples of output voltage waveform. 86
4.45 Resulted ripples of output voltage waveforms due to its double-input voltage sources. 87
4.46 Circuit diagram of double-input buck-boost converter 88
4.47 Simulation model circuit of double-input buck-boost converter 89
4.48 Total input current waveform 90
4.49 Ripples of total input current waveform 90
4.50 Output current waveform 91
4.51 Ripples of output current waveform 91
4.52 Output voltage waveform. 92
4.53 Ripples of output voltage waveform 92
4.54 Resulted ripples of output voltage waveforms due to its double-input voltage sources 93
4.55 Circuit diagram of double-input Z-aource converter 94
4.56 Simulation model circuit of double-input Z-source converter 95
4.57 Total input current waveform 96
4.58 Ripples of total input current waveform 96
4.59 Output current waveform 97
4.60 Ripples of output current waveform 97
4.61 Output voltage waveform 98
4.62 Ripples of output voltage waveform 98
4.63 Resulted ripples of output voltage waveforms due to its double-input voltage sources 99
4.64 Block diagram for overall proposed DIBC. 101
4.65 Open-loop simulation model of the proposed double-input converter circuit using MATLAB Simulink software. 102
4.66 Simulation model of PWM generator block. 102
4.67 Switching signals of switches $S_1, S_2, S_3$ and $S_4$; $[d_1 = d_2 = 0.75; d_3 = d_4 = 0.5]$. 103
4.68 Inductors voltage ($V_{L1}$ and $V_{L2}$); inductors current ($I_{L1}$ and $I_{L2}$); $[d_1 = d_2 = 0.75; d_3 = d_4 = 0.5]$. 104
4.69 Voltage input source ($Vin_1$ and $Vin_2$); output voltage ($V_{out}$); total input inductor current $I_{Lin}$. 105
4.70 Output current $I_{out}$ and output voltage $V_{out}$ in the case matched input voltage sources.

4.71 Switching signals of switches $S_1, S_2, S_3$ and $S_4$ [$d_1 = d_2 = 0.75; d_3 = d_4 = 0.5$].

4.72 Inductors voltage ($V_{L1}$ and $V_{L2}$); inductors current ($I_{L1}$ and $I_{L2}$) [$d_1 = d_2 = 0.75; d_3 = d_4 = 0.5$].

4.73 Voltage input source ($Vin_1$ and $Vin_2$); output voltage ($V_{out}$); total inductor current ($I_{L1} + I_{L2}$).

4.74 Output current $I_{out}$ and output voltage $V_{out}$ in the case mismatched input voltage sources.

4.75 Total input current waveform

4.76 Ripples of total input current waveform

4.77 Output current waveform

4.78 Ripples of output current waveform

4.79 Output voltage waveform

4.80 Ripples of output voltage waveform

4.81 Resulted ripples of output voltage waveforms due to its double-input voltage sources.

4.82 Voltage regulation capability of the proposed converter when the output voltage is commanded from 0V to 40V.

4.83 Current regulation capability of the proposed converter when the output voltage is commanded from 0V to 40V.

4.84 Voltage regulation capability of the proposed converter when the output voltage is commanded from 0V to 60V.

4.85 Current regulation capability of the proposed converter when the output voltage is commanded from 0V to 60V.

4.86 Closed-loop simulation model of the proposed double-input boost converter.

4.87 Simulation model of neural network controller using MATLAB Simulink software.

4.88 Line regulation capability of the proposed double-input converter when input source 1 is stepped down from 24V to 18V.
4.89 Load regulation capability of the proposed double-input converter when the load resistance is stepped down from 10Ω to 5Ω.

4.90 Voltage regulation capability of the proposed converter with single reference testing when the output voltage is commanded from 0V to 40V.

4.91 Voltage regulation capability of the proposed converter with single reference testing when the output voltage is commanded from 0V to 60V.

4.92 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 36V to 45V.

4.94 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 36V to 50V.

4.93 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 45V then step down from 45V to 36V.

4.95 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 50V then step down 50V to 36V.

4.96 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 40V to 50V.

4.97 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 50V then step down from 50V to 40V.

4.99 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 60V then step down from 60V to 45V.

4.98 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 45V to 60V.

4.100 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 55V to 70V.
4.101 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 70V then step down from 70V to 55V.

4.102 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 60V to 80V.

4.103 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 80V then step down from 80V to 60V.

4.104 Prototype of the proposed double-input converter circuit.


4.106 Simulink circuit of close loop circuit using MATLAB Simulink software.

4.107 The experimental set-up of the proposed double-input converter.

4.108 Gate pulses of switches S1, S2, S3 and S4 (Ch1, Ch2, Ch3 and Ch4); [d1 = d2 = 0.75; d3 = d4 = 0.5].

4.109 Inductors voltage V_L1 and V_L2 (Ch1 and Ch2); Inductors current I_L1 and I_L2 (Ch3 and Ch4).

4.110 Voltage input source Vin1 and Vin2 (Ch1 and Ch2); output voltage V_out (Ch3); total input inductor current I_L1 + I_L2 (Ch4).

4.111 Average output voltage V_out (Ch3); average output current I_out (Ch4) in the case matched input voltage sources.

4.112 Gate pulses of switches S1, S2, S3 and S4 (Ch1, Ch2, Ch3 and Ch4); [d1 = d2 = 0.75; d3 = d4 = 0.5].

4.113 Inductors voltage V_L1 and V_L2 (Ch1 and Ch2); Inductors current I_L1 and I_L2 (Ch3 and Ch4).

4.114 Voltage input source Vin1 and Vin2 (Ch1 and Ch2); output voltage V_out (Ch3); total input inductor current I_L1 + I_L2 (Ch4).

4.115 Average output voltage V_out (Ch3); average output current I_out (Ch4).
Conventional double-input boost converter: switching signals of switches $S_1$ and $S_3$ (Ch1); switching signal of switch $S_2$ (Ch2) and output voltage $V_{out}$ (Ch4).

Proposed double-input converter: switching signals of switches $S_3$ and $S_4$ (Ch1 and Ch2); and output voltage $V_{out}$ (Ch4).

Voltage regulation capability of the proposed converter when the output voltage is commanded from 0V to 40V.

Voltage regulation capability of the proposed converter when the output voltage is commanded from 0V to 60V.

Line regulation capability of the proposed double-input converter.

Load regulation capability of the proposed double-input interleaved boost converter.

Voltage regulation capability of the proposed converter with single reference testing when the output voltage is commanded from 0V to 40V.

Voltage regulation capability of the proposed converter with single reference testing when the output voltage is commanded from 0V to 60V.

The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 36V to 45V.

The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 45V then step down from 45V to 36V.

The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 36V to 50V.

The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 40V to 50V.

The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 50V then step down 50V to 36V.
4.129 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 50V then step down from 50V to 40V.

4.130 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 45V to 60V.

4.132 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 55V to 70V.

4.131 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 60V then step down from 60V to 45V.

4.133 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 70V then step down from 70V to 55V.

4.134 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 80V.

4.135 The dynamic response of the proposed double-input converter when the output voltage is commanded to step up from 0V to 80V then step down from 80V to 60V.

E.1 DSP TMS320F28335 real time digital controller.

E.2 Functional block diagram.

F.1 PCB design of the gate driver circuit.

G.1 PCB design of voltage divider circuit.

H.1 Uncoupled inductors using a ferrite EE core.

I.1 Data sheet of IGBT.

J.1 Data Sheet of Diode.

K.1 Data Sheet of Capacitor.
## List of Tables

<table>
<thead>
<tr>
<th>Table No</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Gap of study from several papers and journals of control topologies of double-input DC-DC converters.</td>
<td>37</td>
</tr>
<tr>
<td>3.1</td>
<td>Voltage across the inductors $L_1$ and $L_2$ for different modes.</td>
<td>51</td>
</tr>
<tr>
<td>4.1</td>
<td>Power Stage Parameters of the Designed Converter.</td>
<td>101</td>
</tr>
<tr>
<td>4.2</td>
<td>Ripples analysis comparison for conventional and proposed double-input converter.</td>
<td>114</td>
</tr>
<tr>
<td>4.3</td>
<td>Simulation results comparison for open circuit verification.</td>
<td>152</td>
</tr>
<tr>
<td>4.4</td>
<td>Experimental results comparison for open circuit verification.</td>
<td>153</td>
</tr>
<tr>
<td>4.5</td>
<td>Simulation results comparison for closed-loop verification.</td>
<td>153</td>
</tr>
<tr>
<td>4.6</td>
<td>Experimental results comparison for closed-loop verification.</td>
<td>153</td>
</tr>
</tbody>
</table>
# List of Appendices

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Source Code (C++ Language) of Switching pulse of Switches $S_1$ &amp; $S_2$</td>
<td>169</td>
</tr>
<tr>
<td>B</td>
<td>Source Code (C++ Language) of Switching Pulses of Switches $S_3$ &amp; $S_4$</td>
<td>172</td>
</tr>
<tr>
<td>C</td>
<td>Source Code (C++ Language) of Neural Network Control Algorithm</td>
<td>176</td>
</tr>
<tr>
<td>D</td>
<td>Source Code (C++ Language) of Digital to Analog Converter DAC</td>
<td>180</td>
</tr>
<tr>
<td>E</td>
<td>Digital Signal Controller and Functional Overview</td>
<td>183</td>
</tr>
<tr>
<td>F</td>
<td>Gate Driver Circuit</td>
<td>185</td>
</tr>
<tr>
<td>G</td>
<td>Voltage Divider Circuit</td>
<td>186</td>
</tr>
<tr>
<td>H</td>
<td>Uncoupled Inductors</td>
<td>187</td>
</tr>
<tr>
<td>I</td>
<td>Data Sheet of IGBT</td>
<td>188</td>
</tr>
<tr>
<td>J</td>
<td>Data Sheet of Diode</td>
<td>189</td>
</tr>
<tr>
<td>K</td>
<td>Data Sheet of Capacitor</td>
<td>190</td>
</tr>
</tbody>
</table>
# List of Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Capacitor</td>
</tr>
<tr>
<td>D</td>
<td>Power diode</td>
</tr>
<tr>
<td>fsw</td>
<td>Switching frequency</td>
</tr>
<tr>
<td>I1</td>
<td>Input current source 1</td>
</tr>
<tr>
<td>I2</td>
<td>Input current source 2</td>
</tr>
<tr>
<td>Ic</td>
<td>Capacitor current</td>
</tr>
<tr>
<td>IL</td>
<td>Inductor current</td>
</tr>
<tr>
<td>IL1</td>
<td>Current across inductor 1</td>
</tr>
<tr>
<td>IL2</td>
<td>Current across inductor 2</td>
</tr>
<tr>
<td>L</td>
<td>Inductor</td>
</tr>
<tr>
<td>RL</td>
<td>Output load</td>
</tr>
<tr>
<td>S</td>
<td>Power switch</td>
</tr>
<tr>
<td>T</td>
<td>Switching period</td>
</tr>
<tr>
<td>Toff</td>
<td>Switch off time</td>
</tr>
<tr>
<td>Ton</td>
<td>Switch on time</td>
</tr>
<tr>
<td>V1</td>
<td>Input voltage source 1</td>
</tr>
<tr>
<td>V2</td>
<td>Input voltage source 2</td>
</tr>
<tr>
<td>Vin</td>
<td>Input line voltage</td>
</tr>
<tr>
<td>VL</td>
<td>Voltage across inductor</td>
</tr>
<tr>
<td>VL1</td>
<td>Voltage across inductor 1</td>
</tr>
<tr>
<td>VL2</td>
<td>Voltage across inductor 2</td>
</tr>
<tr>
<td>Vout</td>
<td>Output load voltage</td>
</tr>
<tr>
<td>Vref</td>
<td>Reference voltage</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introduction

In this chapter, introduction of the research will be explained in detail which consists of the research background towards focusing of research study, problem statements, research objectives and scope.

1.2 Research Background

In recent years, hybridization of the energy systems is gaining more and more popularity in the field of electric power system. Hybrid energy system is an emerging technology that has the potential to meet future energy requirements that increases significantly every years. A well designed hybrid energy system provides good power handling capability during steady-state operation and better dynamic response during transient. However, to combine various energy systems together in order to meet the power demand (Cao & Emadi, 2012; Tan et al., 2013), hybrid energy system needs a proper interfacing circuitry to integrate several energy sources that having different V-I characteristic.

Alongside the traditional types of the converters which are able to connect to only one supply of distributed generation, in recent years new types of converters are becoming prominent which are capable of connecting to more than one supply of distributed generation at the same time and whose power get transferred to the output, simultaneously. These converters which are introduced as multi source converters. Multiple source DC-DC converters are playing significant role in interfacing of different energy sources to form hybrid energy system that delivers power at regulated voltage (Jiang & Fahimi, 2011). The energy sources like
fuel cell, battery, ultracapacitor and renewable energy sources of same or different category with distinct V–I characteristic are connected together through Multiple source DC/DC converters to supply the load individually or simultaneously.

Traditionally these energy sources are combined together through a separate single source converter and their outputs are connected to a common dc bus (Tan et al., 2013; Ozaki et al., 2010; Samosir & Yatim, 2010), namely multiple single converter. The energy sources of same or different category with distinct V–I characteristic are traditionally connected together through individual DC-DC converters and their outputs are connected to common dc bus either in series or parallel (Valenciaga & Puleston, 2005; Kumar & Ikkurti, 2011; Wang & Nehrir, 2008; Jiang & Fahimi, 2011; Khaligh et al., 2009) However, such multiple single-input DC-DC converters configuration are costly, bulky and relatively complex in design and reduce overall efficiency as well as reliability of the system. In addition, such configurations produce a high ripple in input side as well as output side and it is difficult to achieve the regulated voltage output.

Multiple single-input DC-DC converters can be successfully replaced by a single multiple-input DC-DC converter. The single multiple-input DC-DC converter offers more compact design and simple and reduces the cost and complexity of the converter system. Besides, effective dc power distribution at regulated output voltage reinforces reliability (Khaligh et al., 2009; Tao et al., 2006; Chen et al., 2002).

The last decade, several isolated and non-isolated DC-DC converter topologies on multiple-input converters have been proposed. The isolated multiple-input converters DC-DC topologies are based on magnetically connected circuit. Thus, the necessity of the extra peripheral circuitry and the transformer requirement make the magnetic-connected circuit have disadvantages such as complicated, huge, expensive, large number of power switches, and complicated controller are needed.

In addition, magnetically connected circuit, flux addition along with time domain multiplexing is a commonly used technique for energy transformation from sources to load (Chen et al., 2006). The mandatory requirement of transformer makes magnetically connected circuit complex, bulky, costly and increases dependency on circuit parameters (Matsuo et al., 2004).

On the other hand, non-isolated multiple-input DC-DC converters topologies are based on electrically connected circuit. Consequently, electrically connected circuit have advantages such as modular structure, low cost and absence of transformer make it attractive and minimises the issues associated with magnetically connected circuit to a large extent (Zhao et al., 2008).

In addition, the modular structure design and no transformer required
make the electrically connected circuit simple, consolidated design, lower cost, high flexibility for voltage output and wide control range of different input powers. The electrically connected multiple-input converters topologies combine various input energy sources either in parallel (Tao et al., 2006; Gummi & Ferdowsi, 2010; Chen et al., 2006) or in series (Chen et al., 2006; Ahmadi & Ferdowsi, 2012).

1.3 Problem Statements

At present, several multi-input DC-DC converter topologies are proposed with improved efficiency and reduced components, however, the issues to reduce the sum of the output ripples have not been taken much consideration. Conventional strategy of connecting multiple energy sources places them either in parallel or series configurations. For the multi-input configuration in parallel connection, the current on the load side is the sum of the current from each converter. While in series connection; the voltage at the load side is the sum of the voltage from each converter. Thus, the voltage and current ripples at the load side increases when the ripples are added up from each converter, which reduces the performance of converter system.

On the other hand, in conventional approaches for two voltage sources connected in series, a control switch has to be provided for each dc voltage source to act as by-pass short-circuit for input current of other supply. Besides, for a parallel connection, because of the difference between two dc voltage amplitudes, only one of the two sources can be connected at a time. Therefore, both series and parallel configurations are very difficult to achieve the desire regulated voltage output.

The major challenges of designing a multi-input DC-DC converter application are how to handle multi-sources with a different value and how to improve the converter parameters such as low current ripple, low voltage ripple, and high efficiency. In this project, a double-input converter with low ripple and high performance has been proposed.

1.4 Research Objective

The objective of this research is to design and develop a double-input boost power converter for electric power applications system. The project proposes a new double-input power converter strategy that is suitable for integrating two energy resources effectively.

The major objectives of this project are:

1. To model and simulate the proposed optimum double-input converter.
2. To design and fabricate a prototype of the proposed double-input converter.

3. To develop a PWM control strategy of the proposed double-input converter.

4. To develop an ANN control algorithm of the voltage regulator controller for the proposed double-input converter.

1.5 Research Scope

This project will be conducted with the following stage:

1. Modeling and simulation:
   - Modelling and simulation of the proposed double-input converter to identifying its electrical characteristic and performance of the converter using Simulink MATLAB.

2. Controller program development:
   - Design and develop of the PWM switching signals and control algorithm of the proposed double-input converter.

3. Hardware and software implementation:
   - Design and fabrication a prototype of the proposed double-input converter.
   - The interface of DSP TMS320F28335 Real-time Digital Signal Controller board for the proposed double-input converter is constructed.

1.6 Research Methodology

In this research, a double-input interleaved boost converter is proposed using the concept of pulsating voltage source cells for synthesis and generation of input sources circuit combined with double inductors interleaved concept as ripple reduction technique.

Based on concept of interleaved technique, the two interleaved inductors $L_1$ and $L_2$ are in parallel operating out of phase which caused by the conduction of switches $S_3$ and $S_4$ in order to provide the interleaved operating mode and boosting level. Thus, the input current $I_n$ is the sum of both inductor currents. As the inductor’s ripple currents are out of phase, they have a tendency to cancel each other and decrease input ripple current as well as output ripple current caused by the boost inductors.

The conduction of main switches $S_1$ and $S_2$ decides input sources delivering power to the load. Thus, by modulating the widths of duty cycles using the proposed neural network control, the amount of power supplied from input voltage sources can be controlled, in order to achieve the desired regulated output voltage.
The voltage regulator controller is designed based on the Artificial Neural Network (ANN) algorithm as a predictor of the control signal (duty cycle) in order to regulate output voltage of proposed converter. The output voltage of the proposed converter system is used as objective function of the proposed converter to regulate it.

The learning capability of ANN makes it suitable for implementation in a system with a range of different operating modes. The Back-propagation learning schemes is implemented for ANN controller. The control signal value is generated depending on the change in parameters such as (.line regulation, load regulation, and output voltage tracking capability).

The goal of this study is to improve the performance of the double-input converter system by using the proposed interleaved topology as ripple reduction technique while at the same time retaining the good performance of output voltage response. In order to verify the validity of the proposed converter design, both simulation and experimental testing has been conducted.

1.7 Thesis Outline

The outlines of the structure for this thesis are given as follow:

- Chapter 2 this chapter begins by discussing the basic concept of DC-DC converter and its control techniques. Then, an overview of the multiple-input DC-DC converter system and review of the previous work is explained. Finally, research gap on previous multi-input converters are presented.

- Chapter 3 in this chapter, the proposed double-input boost converter (DIBC) is discussed. The design of the proposed DIBC involves configuration, switching pattern, components selection and mode of operation. In addition, the prospective of the proposed neural network control implemented on the voltage regulation control are discussed. The control algorithm of the neural network is explained in details.

- Chapter 4 provides the comparative studies on conventional types of double-input DC-DC converters to validate the proposed DIBC. The minutiae explanation for both simulation and hardware implementation in this research. The proposed double-input converter and controller are simulated by using Matlab-Simulink. The experimental hardware setup is controlled through the DSP TMS320F28335 Real-time Digital Signal Controller and interfaced by using the Matlab-Simulink software. In addition, the promising performance of the proposed controller is obtained through simulation and then
verified by the relevant experiment results. Further analysis and discussion on the obtained result are provided.

- Chapter 5. presents the summaries of the contribution of this research and the recommendation for future research direction.
Chapter 2

Literature Review

2.1 Introduction

This chapter begins by discussing the basic concept of DC-DC converter and its control techniques. Then, an overview of the multiple-input DC-DC converter system and review of the previous work is explained. Finally, research gap on previous multi-input converters are presented.

2.2 Overview of Basic DC-DC Converters

In this section, the basic of DC–DC converters are explained in details in the following subsection.

2.2.1 Basic DC Power Converter System

Typically the role of an electrical power converter is to facilitate the transfer of power from source to the load, alongside vice versa, by converting currents and voltages at one specific level to other levels. A DC-DC converter is a power electronic converter that accepts DC input voltages and produce DC output voltages. In the converter, a controller is required to handle power transfer process. Final goal of the complete conversion process is to achieve as closely as possible the required conversion with high performance, and high efficiency (Liu & Lee, 1988). A general DC-DC power converter block diagram is shown in Figure 2.1.
2.2.2 Basic Circuit of DC–DC Converter

Basically, there are three basic configurations of the DC-DC (Liu & Lee, 1988), known as a buck, boost, and buck-boost converters. The three types of DC-DC converters circuit are shown in Figure 2.2.
As shown in Figure 2.2, each of these converters consist of one active power switch $S$ such as for example MOSFET and one passive power switch $D$ such as for example diode. Furthermore the converter circuit offers filter components such as one inductive storage element $L$, and one capacitive storage component $C$. Where, $V_{out}$ is the output voltage, $V_{in}$ is the input voltage, and $R_L$ is the load.

The principal function of the buck converter would be to step-down an input voltage to a lower output voltage, i.e., $V_{out} < V_{in}$. Conversely, the principal functionality of the boost converter would be to step up an input voltage to an increased output voltage, i.e., $V_{out} > V_{in}$. The buck-boost converter, because the name suggests, enables both functions of stepping up and stepping down of the
input voltage (Ogata, 1997).

In the basic DC converters, the magnitude of the voltage conversion is directly controlled by the turning-on and the turning-off of the switch. For the buck converter, the power is directly transferred to the output and the capacitive storage when switch $S$ is turned on. This occurs with the energizing procedure for its inductive storage element concurrently. While, for the buck-boost and boost converters, the particular energizing process occurs when switch $S$ is switched-on. The power will be transferred from the inductive storage to the output, and the capacitive storage happens immediately after switch $S$ is switched-off. This indirect power transfers from the source to the load with inductor.

Additionally, in the presence of two switches, these converters could be visualized as a multi-structural system, in which each structure includes a linear circuit construction (Mitchell, 1988). Modification of the circuit configuration is governed by the settings of the switches and the flow from storage currents.

2.2.3 Basic Operation Modes of DC–DC Converter

There are two operating modes within the buck, boost, and buck-boost converters, namely, the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM) operation. When working in CCM, only two possibilities switch configuration between switch $S$ and diode $D$, i.e. $S$-ON and $D$-OFF or $S$-OFF and $D$-ON. The converters can stay in this working mode so long as the inductive storage is relatively big (Mitchell, 1988). Conversely, if the inductive storage is relatively small, the procedure drops into DCM, leading to three switching states, i.e. $S$-ON and $D$-OFF, $S$-OFF and $D$-ON, and $S$-OFF and $D$-OFF. The particular mode of operation could be identified through inspection from inductor current waveform as shown in Figure 2.3(a).
In the CCM operation, the particular turn-on time of the energetic switch $S$ is denoted as $dT$, where $d$ is the duty ratio and $T$ is the switching time period. Major characteristic of the CCM operation is indicated that the inductor current $I_L$ is always more than zero as shown in Figure 2.3(a).

Figure 2.3(b) shows the inductor current waveform when the converter works in DCM. Where, $dT$ represents time operation when the diode is definitely conducting, and the power switch is open and, $d'T$ represents the time operation when both diode and the switch are open. This time operation could be equivalently indicated as $(1 - d - d')T$.

### 2.2.4 Basic Elements of DC-DC Converter

The size of the capacitive and inductive energy storage tanks, i.e., $C$ and $L$ have an effect on the overall performance of the DC-DC converter. This is often comprehended by examining the particular operating system of these elements. Because the price of storing electricity capacitor $C$ and inductor $L$ directly impacted by the size of the power storage components, the capability to react to load changes will therefore be impacted by the size of the power storages. In par-
ticular, for a fixed-frequency operation, the dynamic response of the regulation is going to be quicker with smaller values of $C$ or $L$, since smaller power storage elements need a shorter time to release and store power (Ogata, 1997).

However, a smaller value of $L$ will certainly result in a higher ripple inductor current and lower output voltage undershoot or overshoot during a step increment or decrement in load current. Nevertheless, a bigger value of $C$ gives lower output voltage undershoot during a step increment in load current, and lower output voltage overshoot during a step decrement in load current. Each one of these aspects forms dynamic behavior of the converter response.

### 2.2.5 Basic Switching Frequency of DC-DC Converter

In theory, ideal performance is achievable only when switching frequency is infinitely high. The term ideal performance means perfect DC steady-state regulation, fast dynamic response infinitely, and no overshoot. Nevertheless, since all useful systems are put through time delays and slew rate restrictions in circuit elements, a higher switching frequency procedure is infinitely unattainable.

The particular magnitude of switching frequency is tied to bandwidths of the circuit elements consequently, i.e., the controller, power switch, diode, etc. Additionally, it is known that the amount of power loss in converter rises with the increment of switching frequency. That is true even though soft-switching methods are applied to alleviate the switching losses of the power switches and diodes. Eddy current and current hysteretic losses of magnet elements and resistive power losses of the circuit because of skin effect increases with the increment of switching frequency (Ogata, 1997).

By this reason, each one of these losses could be less than the losses generated by the switches relatively. Nonetheless, it must be a consideration whenever determining switching frequency of the converter given that they will become significant once the frequency is extremely high. Additionally, the emission of higher frequency noise could cause undesirable radio and electromagnetic interferences. Such noise will be the factors that restrict achievable application of extremely fast switching frequency controller to gain an ideal regulation.

Selecting the switching frequency should always be considered a choice of balancing between achieving desired control to meet consumer specifications and reducing power losses, power density, and EMI emission. However, it is true that the performance of the converter can be continually enhanced with an increased switching frequency (Mitchell, 1988).

The noise can be removed by fixed frequency operation. With appropriate filtering, grounding, bonding, and shielding, switching converters can be successfully used in EMI-sensitive applications (Ogata, 1997).
2.2.6 Basic Voltage Regulation of DC-DC Converter

Many DC-DC converters were created with closed-loop feedback controller to provide a regulated output voltage. There are two types of elements in the feedback control scheme, the controlled variable and control gains. The controlled variable is the variable to be controlled (Mitchell, 1988).

In the DC-DC converter, controlled variable is the output voltage and the inductor current. The primary objective, from the perspective of the controller, is to guarantee nullification of the output voltage errors or the inductor current errors for any disturbance, in a well-balanced manner in shortest period. This is carried out through manipulation of controlled variable, by adopting its immediate, essential, and/or derivative types because the manipulated variables in its control computation (Tse & Adams, 1990).

The objective of control gains is a multiplication factor to amplify these manipulated variables, so the integrity of the manipulated variables could be intensified. This gives shaping of the controlled behavior in a way that required response can be achieved.

Fixed-frequency pulse-width-modulation (PWM) control is undoubtedly the most famous control technique useful for regulation of DC-DC converters. Two reasons for this design are the availability of extremely low-cost sophisticated fixed-frequency PWM controllers, and minimize the emissions of switching converters in more sensitive electric conductivity environments (Liu & Lee, 1988). Equivalent circuit of the voltage mode control of the DC converter is shown in Figure 2.4.
The voltage mode control is a single-loop control where, in fact, the output voltage is regulated by closing a feedback loop between output voltage and duty ratio signal. The output voltage is compared with a constant reference signal $V_{\text{ref}}$ to provide voltage errors, which is after that passed through the compensation network to generate a control signal (Mitchell, 1988). The PWM modulator receives compensated control signal to generate the required switching signal for driving power switch. An input voltage feed forwards scheme is required to increase the immunity of converter output voltage against disturbances in input voltage.

2.3 Overview of Multiple-input DC-DC Converter System

Traditional approach of connecting multiple energy sources is placing them either in series or parallel with one another. However, these techniques have some limitations such as, for the sources that are put into series, need to conduct exactly the same current that is not always desirable. Moreover, when different sources have different voltage levels, they cannot be connected in parallel directly (Glavin & Hurley, 2006).
2.3.1 Parallel-Single Input Converters

Figure 2.5 shows the block diagram of an operational system in which converters is connected in parallel. Individual DC-DC conversion levels are used for individual sources (Ozpínci et al., 2004; Haque et al., 2006; Di Napoli et al., 2002; Solero et al., 2005; Lidozzi & Solero, 2004; Amirabadi & Farhangi, 2006; Camara et al., 2006). These converters are linked together at the DC bus and controlled independently. In some operational systems, a communication bus could include information and manage power flow between the sources. Various types of such converters are the current-fed push-pull converter, phase-shifted full-bridge converter, three-phase converter, etc. The main drawback of such system is inherently complicated and needs higher cost because of the multiple conversion stages and communication devices between individual converters (Tao et al., 2006).

![Figure 2.5: Parallel-connected converter (Camara et al., 2006).](image_url)
2.3.2 Series-Single Input Converters

A block diagram of series connected converters is shown in Figure 2.6. This configuration is used in low power wind generator and solar panel applications (Chan, 2002, 2007; Chan et al., 1993). In this circuit configuration, output voltage and current regulation are difficult to be controlled since both the sources used could have intermittent character (Chan & Chau, 1997; Marwali et al., 2000; Glavin & Hurley, 2006). The main drawbacks of such systems are that output current flows through both converters and therefore power loss is high (Hirachi et al., 1995; Sopitpan et al., 2000). Furthermore, gating signals for both input voltage sources are conjunctive which might create a circulating current in the two input sources.

![Figure 2.6: Series-connected converters (Camara et al., 2006).](image)

2.3.3 Multi-input Converter System

A multi-input DC-DC converter is a converter having more than one energy source as its input. This system results in less components, simple control, more stability, and also reduce losses in the system. Furthermore, the efficiency of power distribution are reinforced dependability at the regulated output voltage (Camara et al., 2006). The basic block diagram of the multi-input converter is shown in Figure 2.7. This system includes a single multi-input converter rather than using two separate converters.
2.4 Review of Multi-Input DC-DC Converters

The multiple-input converter is one of the best candidates for renewable energy applications since it can harvest and process power from different sources and energy storages. Multiple-input topology has the advantages of low cost, high power density and ease of management. There have been extensive researches on multiple-input converter in recent years which has resulted in wide spectrum of topologies. Multiple-input converter can be classified into two categories, namely magnetically coupled converter (isolated) and electrically coupled converter (non-isolated).

2.4.1 Previous Works of Isolated Multi-Input DC-DC Converters

In general, isolated multi-input DC–DC converters use leakage inductance as energy storage for transferring power between two sides of the converters. Therefore, the power flow between input and output sides is controlled by adjusting the phase shift angle between primary and secondary voltages of transformer (Camara et al., 2006). According to converter topology, time domain multiplexing, flux addition, and magnetic energy transfer methods are applied in isolated multi-input converters to transfer energy from the primary side of the converter to the secondary (Li et al., 2007).

A general Flyback forward converter based on multiple-input topology to couple energy is shown in Figure 2.8. It was one of the initial versions of isolated multi-input DC–DC converters using time domain multiplexing technique (Zhao et al., 2011; Kuo et al., 2010; Lin et al., 2009; Chung et al., 2010; Oliveira & Barbi, 2011; Michon et al., 2004; Duarte et al., 2007; Tao et al., 2008b).
Time domain multiplexing in isolated flyback multi-input DC–DC converters is easy to be implemented; however, the energy quantity of such topologies is insufficient due to the nature of Flyback/forward topology. In addition, flyback multi-input converters with winding topology have disadvantages such as, needing of a high-value output capacitor, the high current stress in the power switch, high eddy current loss in air-gap area, a large transformer core, and potential EMI problems (Kuo et al., 2010; Lin et al., 2009).

Isolated multi-input DC–DC converters based on flux addition principles with concept of half-bridge isolated converters, full-bridge isolated converters, boost half-bridge isolated converters, and combinational multi-port isolated converters as shown in Figure 2.9 and Figure 2.10. Energy from different sources is transferred to secondary by adding total flux in magnetic core from each conversion channel (Tao et al., 2008a; Krishnaswami & Mohan, 2009; Wang et al., 2011; De Doncker et al., 1991; Mi et al., 2008; Wai et al., 2009; Yan et al., 2009).
Another approach of the multi-input full-bridge converter as shown in Figure 2.11, which based on flux addition of transformer (Chen et al., 2004, 2002). Two full-bridge cells are coupled together by a transformer with two primary windings and a secondary winding, sharing rectifier diodes and filter capacitor to power the loads (Chen et al., 2001; Matsuo et al., 1998). The full-bridge cells have feature of soft-switching. However, a large number of power switches are required as well as complex control circuit. Thus, the cost of converter will be increased.
Figure 2.12: Isolated multiple-input with two full-bridge DC-DC converter (Chen et al., 2001).

The current-fed multi-input DC-DC converter as shown in Figure 2.12, energy from different power sources can be transferred simultaneously to the load through a multi-winding transformer (Caricchi et al., 1993). But still an issue of using a large number of switches and concept of using a multi-winding transformer to transfer energy to the load, thus requiring high cost and needing large size for this converter.
A high step-up isolated converter with two input sources was investigated, and the converter utilizes the current-source type applying to both of the input power sources is shown in Figure 2.13 (Liu & Li, 2005). To avoid voltage switching spikes caused by the leakage inductor, an active clamping circuit is added. However, a large number of power switches are required which cause high cost.
2.4.2 Previous Works of Non-Isolated Multi-Input DC-DC Converters

The power flow control of non-isolated multi-input DC-DC converters is relatively straightforward, and their peripheral circuit is usually simple (Marchesoni & Vacca, 2007; Kim et al., 2011). Although non-isolated multi-input DC-DC converters have high flexibility for voltage output, modular structure, and lower cost make non-isolated multi-input converters more favorable in a variety of applications such as renewable energy power station and automotive systems (Spiazzi et al., 2010; Park et al., 2010; Vazquez et al., 2007).

A general non-isolated multi-input DC-DC converter using H-bridge structure is shown in Figure 2.14 (Prabhala et al., 2009). The cascading two H-bridges with different DC-link voltages, different voltages due to addition or subtraction of H-bridges outputs are accessible.

![Multi-input converters derived from H-bridge structure](Ahmadi & Ferdowsi, 2012).
The advantage of these converters is its less number of passive elements, and its disadvantage is an unsuitable control on the power that is drawn from input sources. Moreover, this converter has high output current ripple due to ripple added from both input voltage sources.

A multi-input DC–DC buck and boost converters are introduced (Li et al., 2009; Gummi & Ferdowsi, 2010). This converter consists of paralleling two buck converter in their inputs. One switch is series to each input source to prevent short circuit of sources. Figure 2.15 shows a multi-input DC-DC converter with battery/ultra-capacitor for electric vehicle applications.

Figure 2.15: Multiple input DC-DC converter with battery/ultra-capacitor (Li et al., 2009).

The advantage of this converter is reducing the number of inductors and capacitors that in turn lead to a reduction in cost, volume, and weight of the converter. Nevertheless, lack of proper power flow control between inputs sources with each other is a weakness of the proposed converter. Additionally, in these converters a high input ripple added from both voltage sources; thus, leading to high output current ripples.
A multi-input Z-source DC–DC converter is shown in Figure 2.16 (Sedaghati & Babaei, 2011). The structure of proposed converter is changed such that the number of inductors and capacitors is equal to a single input z-source converter. However, two inductors and a capacitor are applied in the proposed converter making the design bulky and costly.

![Multi-Input Z-Source DC-DC converter](image)

Figure 2.16: Multi-Input Z-Source DC-DC converter (Sedaghati & Babaei, 2011).

A four-phase bidirectional Flyback converter is shown in Figure 2.17 (Bhattacharya et al., 2009). In this converter, each of the energy sources can deliver or absorb energy from the load and other sources. Employment of a separate inductor for each input source is the drawback of this converter.

![Multiple-input with four-phase bidirectional flyback converter](image)

Figure 2.17: Multiple-input with four-phase bidirectional flyback converter (Bhattacharya et al., 2009).
References


