

**DESIGN, ANALYSIS AND IMPLEMENTATION OF
BIDIRECTIONAL DC-DC CONVERTER**

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DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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**DESIGN, ANALYSIS AND IMPLEMENTATION OF
BIDIRECTIONAL DC-DC CONVERTER**

by

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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

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Certificate

This is to certify that the work presented in the dissertation entitled **Design, Analysis and Implementation of Bidirectional DC-DC Converters** submitted by **Ambuj Sharma**, for the award of the **Doctor of Philosophy** is a record of original research work carried out by him in Department of Electrical Engineering, Indian Institute of Technology Delhi.

Ambuj Sharma has worked under our guidance and supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The matter embodied in this dissertation has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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Abstract

This research work focuses on non-isolated DC-DC bidirectional converters (BDCs), which are suitable for low, medium, and high power applications such as satellite power supplies, battery based applications, and integration of renewable energy sources with a microgrid. These applications operate at different voltage levels depending upon the power levels of the applications. In all the above mentioned applications, DC buses of different voltage levels are used to supply various types of connected loads, but, these voltage levels have to be regulated in a stringent manner for the loads to function properly. The exchange of power between the DC buses happens as per the loading conditions and voltage profiles. To facilitate the exchange of power in both (i.e., forward and reverse) directions, BDCs are used in between these dc buses.

This thesis deals with the development and analysis of non-isolated DC-DC bidirectional topologies, improvement in their transient operations during start-up and change of direction of power flow (mode-transition), and converter current control on the low voltage side. Different non-isolated DC-DC bidirectional topologies are evolved to meet a wide range of load power requirements. In this work, two different bi-directional converter topologies have evolved, which are suitable for charging/discharging of secondary batteries: (i) a current-current type bidirectional converter is developed for the transfer of power between two batteries of different voltage magnitudes, and (ii) a multi-functional bidirectional converter. This multi-functional converter effectively realizes buck, boost, non-inverting buck-boost, and inverting buck-boost conversion processes.

These bidirectional converters need smooth start-up and mode transition, i.e. bucking to boosting or vice-versa. In this work, two different transition techniques (i.e., an improved PWM blocking technique and switched inductor technique) are proposed for the current-current BDC and multi-functional BDC. One more transition technique, namely, switched voltage source technique, is proposed for the dual active bridge (DAB) based bidirectional converter. Apart from this, another simple-to-implement transition technique is proposed for the conventional BDCs (i.e., synchronous buck converter and non-inverting buck-boost converter).

Both steady-state and dynamic analyses are established for the proposed bidirectional converters and also for the conventional bidirectional converters with output port having a voltage source instead of a resistance. The state-space average models and switch averaging

techniques are employed to carry out the dynamic analysis of the proposed bidirectional converters. The conditions for continuous conduction mode, discontinuous conduction mode, and boundary conduction mode operations are identified for both, newly developed as well as conventional BDCs, with voltage source connected at the output port.

The newly developed bidirectional converter topologies, proposed transition techniques, proposed PWM schemes, steady-state and dynamic analyses have been validated in simulation using MATLAB and PSIM simulation tools. Further, all these simulated results have been verified experimentally for 1.5 kW output power in the laboratory prototype.

सार

यह शोध कार्य नॉन-आइसोलेटेड डीसी-डीसी द्विदिश कन्वर्टर (बीडीसी) पर केंद्रित है, जो निम्न, मध्यम और उच्च शक्ति अनुप्रयोगों जैसे उपग्रह बिजली की आपूर्ति, बैटरी आधारित अनुप्रयोगों और माइक्रोग्रिड के साथ अक्षय ऊर्जा स्रोतों के एकीकरण के लिए उपयुक्त हैं। ये अनुप्रयोग अनुप्रयोगों के शक्ति स्तरों के आधार पर विभिन्न वोल्टेज स्तरों पर कार्य करते हैं। उपरोक्त सभी अनुप्रयोगों में, विभिन्न वोल्टेज स्तरों की डीसी बसों का उपयोग विभिन्न प्रकार के कनेक्टेड लोड की आपूर्ति के लिए किया जाता है, लेकिन लोड को ठीक से काम करने के लिए इन वोल्टेज स्तरों को कड़े तरीके से विनियमित किया जाना है। डीसी बसों के बीच बिजली का आदान-प्रदान लोडिंग की स्थिति और वोल्टेज प्रोफाइल के अनुसार होता है। दोनों दिशाओं में (यानी, ऊर्जा भंडारण और वितरण में) बिजली के आदान-प्रदान की सुविधा के लिए, इन डीसी बसों के बीच बीडीसी का उपयोग किया जाता है।

यह थीसिस नॉन-आइसोलेटेड डीसी-डीसी द्विदिश टोपोलॉजी के विकास और विश्लेषण से संबंधित है, स्टार्ट-अप के दौरान उनके क्षणिक संचालन में सुधार और बिजली प्रवाह (मोड-संक्रमण) की दिशा में परिवर्तन, और कम वोल्टेज पक्ष पर कनवर्टर करंट नियंत्रण। विभिन्न नॉन-आइसोलेटेड डीसी-डीसी द्विदिश टोपोलॉजी लोड बिजली आवश्यकताओं की एक विस्तृत श्रृंखला को पूरा करने के लिए विकसित किए गए हैं। इस काम में, दो अलग-अलग द्वि-दिशात्मक कनवर्टर टोपोलॉजी विकसित हुई हैं, जो माध्यमिक बैटरी को चार्ज/डिस्चार्ज करने के लिए उपयुक्त हैं: (i) विभिन्न वोल्टेज परिमाण की दो बैटरी के बीच बिजली के हस्तांतरण के लिए एक करंट-करंट प्रकार द्विदिश कनवर्टर विकसित किया गया है, और (ii) एक बहु-कार्यात्मक द्विदिश कनवर्टर। यह बहु-कार्यात्मक कनवर्टर प्रभावी रूप से बक, बूस्ट, नॉन-इनवर्टिंग बक-बूस्ट, और इनवर्टिंग बक-बूस्ट रूपांतरण प्रक्रियाओं को प्रभावी ढंग से संचालित करता है।

इन द्विदिश कन्वर्टर को सुचारू स्टार्ट-अप और मोड ट्रांज़िशन की आवश्यकता होती है, अर्थात् बकिंग टू बूस्टिंग या इसके विपरीत। इस काम में, करंट-करंट बीडीसी और बहु-कार्यात्मक बीडीसी के लिए दो अलग-अलग संक्रमण तकनीकों (यानी, एक बेहतर पीडब्लूएम ब्लॉकिंग तकनीक और स्विचड इंडक्टर तकनीक) प्रस्तावित हैं। एक और संक्रमण तकनीक, अर्थात् स्विचड वोल्टेज स्रोत तकनीक, ड्यूल एक्टिव ब्रिज (डीएबी) आधारित द्विदिश कनवर्टर के लिए प्रस्तावित है। इसके अलावा, पारंपरिक बीडीसी (यानी, सिंक्रोनस बक कन्वर्टर और नॉन-इनवर्टिंग बक-बूस्ट कन्वर्टर) के लिए एक और सरल-से-कार्यान्वयन संक्रमण तकनीक प्रस्तावित है।

स्टैडी-स्टेट और गतिशील विश्लेषण दोनों प्रस्तावित द्विदिश कन्वर्टर के लिए स्थापित किए गए हैं और पारंपरिक द्विदिश कन्वर्टर के लिए आउटपुट पोर्ट के साथ प्रतिरोध के बजाय वोल्टेज स्रोत हैं। स्टेट-स्पेस औसत मॉडल और स्विच औसत मॉडल तकनीक प्रस्तावित द्विदिश कन्वर्टर के गतिशील विश्लेषण करने के लिए कार्यरत हैं। आउटपुट पोर्ट से जुड़े वोल्टेज स्रोत के साथ, नए विकसित और पारंपरिक बीडीसी दोनों के लिए निरंतर चालन मोड, असंतत चालन मोड और सीमा चालन मोड संचालन की शर्तों की पहचान की जाती है।

मैटलैब और पीसिम सिमुलेशन टूल का उपयोग करके सिमुलेशन में नए विकसित द्विदिश कनवर्टर टोपोलॉजी, प्रस्तावित संक्रमण तकनीक, प्रस्तावित पीडब्लूएम योजनाएं, स्टैडी-स्टेट और गतिशील विश्लेषण मान्य किए गए हैं। इसके अलावा, इन सभी सिमुलेशन परिणामों को प्रयोगशाला प्रोटोटाइप में 1.5 kW आउटपुट पावर के लिए प्रयोगात्मक रूप से सत्यापित किया गया है।

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List of Symbols

α	Condition for DCM operation
Δ	Change in magnitude
\tilde{i}_L	Perturbation in inductor current
\tilde{d}	Perturbation in duty
\tilde{v}_c	Change in controller reference
\tilde{i}_{error}	Change in controller input
$i(\infty)$	Current at time $t = \text{infinity}$
τ	Inductor time constant