

EFFICIENCY IMPROVEMENT OF TWO-STAGE ELECTRIC VEHICLE POWERTRAIN

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Efficiency Improvement of Two-Stage Electric Vehicle Powertrain

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Certificate

This is to certify that the thesis titled "**Efficiency Improvement of Two-Stage Electric Vehicle Powertrain**", submitted by **Mr. Mohammad Saleh Khan**, to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision and guidance.

Mr. Mohammad Saleh Khan has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



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Abstract

Electric vehicle (EV) powertrains must maintain high efficiency across wide voltage and power ranges to achieve high power density and extended vehicle range. This thesis explores two-stage EV powertrain configurations and proposes three-phase unfolding as an innovative alternative to conventional pulse width modulation (PWM) based motor drives. Additionally, novel non-isolated topologies for the dc-dc stage are introduced using input-parallel output-series (IPOS) connections of basic modules.

A three-phase unfolding-based powertrain is presented to replace the conventional system comprising a bidirectional boost dc-dc converter and a two-level voltage source inverter (VSI). While traditional systems rely on high-frequency PWM switching in both stages, the unfolding approach employs a high-frequency dc-dc stage to generate piecewise sinusoidal dc-link voltages. These voltages are then unfolded into sinusoidal three-phase ac voltages by a three-level inverter operating at the fundamental frequency, significantly reducing inverter switching losses.

This thesis introduces a non-isolated dc-dc stage for the unfolding system integrating a non-inverting buck-boost (NIBB) converter and a voltage balancer circuit. Analysis reveals that the balancer circuit processes only a fraction of the total power, reducing component size and minimizing losses compared to systems with two isolated full-power processing converters. The analysis and operation of the proposed unfolding based powertrain are validated on a 5 kW SiC-based prototype employing speed sensorless field oriented control on an induction machine.

A detailed efficiency comparison with conventional two-stage motor drives highlights significant loss reduction in the unfolding-based system due to low-frequency inverter switching and partial power handling by the balancer circuit. The unfolding approach also eliminates high-frequency components in the motor common-mode voltage, effectively mitigating damaging common-mode currents. Furthermore, the highly sinusoidal line-line voltages generated by the unfolding system eliminate motor terminal overvoltage issues, even with long

cables. These advantages were validated through both simulations and experiments.

In addition to the unfolding system, this thesis investigates novel IPOS buck-boost converter topologies tailored for the dc-dc stage. The IPOS connection is especially suited for the wide voltage range encountered in powertrain applications. A symmetric IPOS configuration with two NIBB modules is proposed, demonstrating reduced semiconductor and passive component stress while offering high-gain. Strategic module deactivation at low output voltages is used to further enhance efficiency. Comparative analysis shows superior switch utilization, lower filter energy ratings, and higher efficiency than conventional buck-boost designs. The operation, control, and efficiency of the proposed system is validated on a 5 kW prototype with peak efficiencies exceeding 98%.

Lastly, an improved asymmetric IPOS buck-boost converter topology is introduced, combining an NIBB module with a boost module. A seamless mode transition control strategy is developed to optimize performance based on voltage gain requirements. Compared to a standalone NIBB converter, the asymmetric design achieves higher efficiency using lower-rated devices while maintaining comparable filter size. A 24 kW three-phase interleaved prototype is developed with measured efficiencies exceeding 99% across an output voltage range of 250–800 V, affirming its suitability for high-performance EV powertrains.

सार

इलेक्ट्रिक वाहन पावरट्रेन को उच्च शक्ति घनत्व और वाहन की विस्तारित रेंज प्राप्त करने के लिए विस्तृत वोल्टेज और पावर रेंज में उच्च दक्षता बनाए रखनी चाहिए। यह थीसिस टू-स्टेज इलेक्ट्रिक वाहन पावरट्रेन कॉन्फिगरेशन का अन्वेषण करती है और पारंपरिक पल्स विड्थ मॉड्यूलेशन आधारित मोटर ड्राइव के एक अभिनव विकल्प के रूप में 'थ्री-फेज अनफोल्डिंग' (three-phase unfolding) का प्रस्ताव देती है। इसके अतिरिक्त, बेसिक मॉड्यूलस के इनपुट-पैरेलल आउटपुट-सीरीज कनेक्शन का उपयोग करके डीसी-डीसी चरण के लिए नवीन नॉन-आइसोलेटेड टोपोलॉजी पेश की गई है।

एक थ्री-फेज अनफोल्डिंग-आधारित पावरट्रेन को पारंपरिक सिस्टम (जिसमें एक बिडायरेक्शनल बूस्ट डीसी-डीसी कन्वर्टर और टू-लेवल वोल्टेज सोर्स इन्वर्टर होता है) को बदलने के लिए प्रस्तुत किया गया है। जहाँ पारंपरिक सिस्टम दोनों चरणों में हाई-फ्रीक्वेंसी पीडब्ल्यूएम स्विचिंग पर निर्भर करते हैं, वहीं अनफोल्डिंग दृष्टिकोण 'पीसवाइज साइनुसोइडल डीसी-लिंक वोल्टेज' उत्पन्न करने के लिए हाई-फ्रीक्वेंसी डीसी-डीसी चरण का उपयोग करता है। इन वोल्टेज को मौलिक आवृत्ति पर चलने वाले थ्री-लेवल इन्वर्टर द्वारा साइनुसोइडल थ्री-फेज एसी वोल्टेज में 'अनफोल्ड' किया जाता है, जिससे इन्वर्टर के स्विचिंग लॉस में महत्वपूर्ण कमी आती है।

यह शोध प्रबंध अनफोल्डर सिस्टम के लिए एक नॉन-आइसोलेटेड डीसी-डीसी चरण पेश करता है जो एक नॉन-इनवर्टिंग बक-बूस्ट (एनआईबीबी) कन्वर्टर और एक वोल्टेज बैलेंसर सर्किट को एकीकृत करता है। विश्लेषण से पता चलता है कि बैलेंसर सर्किट कुल पावर के केवल एक अंश को संसाधित करता है, जिससे दो आइसोलेटेड फुल-पावर प्रोसेसिंग कन्वर्टर वाले सिस्टम की तुलना में घटकों का आकार और लॉस कम हो जाता है। प्रस्तावित अनफोल्डिंग आधारित पावरट्रेन के विश्लेषण और संचालन को इंडक्शन मशीन पर 'स्पीड सेंसरलेस फील्ड ओरिएंटेड कंट्रोल' का उपयोग करते हुए 5 kW SiC-आधारित प्रोटोटाइप पर सत्यापित किया गया है।

पारंपरिक टू-स्टेज मोटर ड्राइव के साथ विस्तृत दक्षता तुलना, लो-फ्रीक्वेंसी इन्वर्टर स्विचिंग और बैलेंसर सर्किट द्वारा आंशिक पावर हैंडलिंग के कारण अनफोल्डिंग-आधारित सिस्टम में महत्वपूर्ण लॉस की कमी को उजागर करती है। अनफोल्डिंग दृष्टिकोण मोटर कॉमन-मोड वोल्टेज में हाई-फ्रीक्वेंसी घटकों को भी समाप्त करता है, जिससे हानिकारक कॉमन-मोड धाराओं को प्रभावी ढंग से कम किया जा सकता है। इसके अलावा, अनफोल्डिंग सिस्टम द्वारा उत्पन्न अत्यधिक साइनुसोइडल लाइन-टू-लाइन वोल्टेज लंबे केबलों के साथ भी मोटर टर्मिनल ओवर-वोल्टेज की समस्याओं को समाप्त करते हैं। इन लाभों को सिमुलेशन और प्रयोगों दोनों के माध्यम से सत्यापित किया गया है।

अनफोल्डिंग सिस्टम के अलावा, यह थीसिस डीसी-डीसी चरण के लिए तैयार की गई नवीन आईपीओएस बक-बूस्ट कन्वर्टर टोपोलॉजी की जांच करती है। आईपीओएस कनेक्शन विशेष रूप से पावरट्रेन अनुप्रयोगों में आने वाली विस्तृत वोल्टेज रेंज के लिए उपयुक्त है। दो एनआईबीबी मॉड्यूल्स के साथ एक सममित आईपीओएस कॉन्फिगरेशन प्रस्तावित किया गया है, जो उच्च गेन प्रदान करते हुए सेमीकंडक्टर और पैसिव घटकों पर दबाव को कम करता है। दक्षता को और बढ़ाने के लिए कम आउटपुट वोल्टेज पर रणनीतिक 'मॉड्यूल डीएक्टिवेशन' का उपयोग किया जाता है। तुलनात्मक विश्लेषण पारंपरिक बक-बूस्ट डिजाइनों की तुलना में बेहतर स्विच उपयोग, निम्न फिल्टर ऊर्जा रेटिंग और उच्च दक्षता प्रदर्शित करता है।

अंत में, एक उन्नत असममित आईपीओएस बक-बूस्ट कन्वर्टर टोपोलॉजी पेश की गई है, जो एक एनआईबीबी मॉड्यूल को बूस्ट मॉड्यूल के साथ जोड़ती है। वोल्टेज गेन की आवश्यकताओं के आधार पर प्रदर्शन को अनुकूलित करने के लिए एक निर्बाध 'मोड ट्रांजिशन कंट्रोल' रणनीति विकसित की गई है। एक स्टैंडअलोन एनआईबीबी कन्वर्टर की तुलना में, असममित डिजाइन तुलनीय फिल्टर आकार बनाए रखते हुए लो-रेटेड उपकरणों का उपयोग करके उच्च दक्षता प्राप्त करता है। 250–800 V की आउटपुट वोल्टेज रेंज में 99% से अधिक मापी गई दक्षता के साथ एक 24 kW थ्री-फेज इंटरलीव्ड प्रोटोटाइप विकसित किया गया है, जो उच्च प्रदर्शन वाले इलेक्ट्रिक वाहन पावरट्रेन के लिए इसकी उपयुक्तता की पुष्टि करता है।

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