論文 / 著書情報
Article / Book Information

題目(和文)	車載電力貯蔵システムへの適用を目的とした補助変換器を用いた非絶縁型チョッパ回路に関する研究
Title(English)	Study of non-isolated bidirectional choppers with auxiliary converters for onboard energy storage systems
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出典(和文)	学位:博士(学術), 学位授与機関:東京工業大学, 報告番号:甲第12129号, 授与年月日:2021年9月24日, 学位の種別:課程博士, 審査員:萩原 誠,千葉 明,藤田 英明,竹内 希,清田 恭平,三浦 友史
Citation(English)	Degree:Doctor (Academic), Conferring organization: Tokyo Institute of Technology, Report number:甲第12129号, Conferred date:2021/9/24, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Study of Non-Isolated Bidirectional Choppers with Auxiliary Converters for Onboard Energy Storage Systems

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A dissertation submitted to the Department of Electrical and Electronic Engineering of Tokyo Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical and Electronic Engineering

August 2021

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Summary

The recent developments in energy-storage technologies have led to their utilization in various applications ranging from power systems to consumer electronics. Nowadays, energy storage systems are being extensively investigated for utilization in transportation applications as there is a large-scale shift to electrified means of transportation such as electric vehicles and electric railways.

Energy storage systems in electrified railways can be divided into two types: wayside energy storage systems and onboard energy storage systems. In general, these energy storage systems can be based on lithium-ion batteries, nickel-metal hydride batteries, ultracapacitors, fuel cells, flywheels, and a combination of them. The power exchange between railway vehicles and the wayside energy storage systems is restricted by the existence of the current collectors that limit the current and the resistance of the return conductors that cause voltage drops. Onboard energy storage systems help in avoiding these constraints. In addition, onboard

energy storage systems feature higher efficiency and simpler energy management compared with the wayside energy storage system.

Typically, dc electrification systems with voltages ranging from 600 V to 3 kV are adopted in dc electric railways with proposals to extend this range up to 9 kV. A bidirectional chopper is required for voltage conversion between the voltage level of the catenary and that of the battery. Battery energy storage systems that are placed inside the dc electric railways allow the regenerative energy to be stored during braking and reused when it is required, which increases the energy efficiency of the vehicle. However, additional mass and volume resulted from the installation of an onboard energy storage system increase the amount of energy required to run the vehicle due to the extra vehicle mass. To improve the energy efficiency of the vehicle, the amount of energy saving obtained from the reuse of the regenerative energy must exceed the additional energy required to run the vehicle. Therefore, a reduction in the mass of the energy storage system along with its associated power converters is necessary.

In addition to the concerns related to the mass and volume of the energy storage systems, high-power choppers suffer from bulky and heavy magnetics. It is difficult to downsize the bidirectional chopper by increasing the switching frequency since the operating switching frequencies are limited because of the limitation of the power losses in the power devices. For example, the switching frequency of 3.3 kV silicon insulated-gate bipolar transistor (Si-IGBTs) is typically set to less than one kilohertz for reducing switching loss. It is required to reduce the mass and volume of the onboard bidirectional chopper since the mass affects the driving range while the volume affects the flexibility of the vehicle design. The mass and volume of the chopper strongly depend on those of the high-power inductor, which can be the single bulkiest, and heaviest component in the converter system.

The main objective of this dissertation is to propose different topologies of bidirectional choppers that are suitable for onboard battery energy storage systems. The proposed choppers should have a lower mass and volume compared with the conventional alternatives. For achieving this objective, this dissertation proposes an interleaved bidirectional chopper with auxiliary converters (IBCAC) that is in-

tended for its application to onboard battery energy storage systems in dc electric railways when the voltage of the catenary is always higher than the voltage of the battery storage. The proposed chopper can achieve the same peak-to-peak ripple current as that produced by the conventional interleaved chopper using smaller current-smoothing inductors. A smoother high-voltage-side current can be obtained because of interleaving, which further reduces the mass and volume of the magnetics required for current smoothing. Moreover, the proposed chopper can interrupt fault currents at the low-voltage side. Hence, mechanical circuit breakers at the low-voltage side can be removed. If the battery energy storage system operates at voltages that go above and below the catenary voltage, it becomes mandatory to utilize a two-quadrant chopper, where the chopper for the onboard battery energy storage system is required to achieve multi-mode operation, including buck-mode operation, boost-mode operation, and buck-boost mode operation. For this purpose, this dissertation proposes a compact non-inverting bidirectional buck-boost chopper (NIBAC) for installation inside a railway vehicle.

In addition to the proposed topologies, a modified phase-shifted pulse width modulation (PSPWM) method has been proposed for application to the IBCAC. The modified PSPWM can significantly reduce the current ripple at the low-voltage side compared with the conventional PSPWM, which eventually results in further miniaturization of the chopper. The proposed topologies, the associated control systems, and the pulse width modulation schemes for the proposed choppers are experimentally validated in this dissertation using down-scaled prototypes. Further, comparisons with commonly used converter topologies have shown that the proposed choppers are significantly smaller and lighter than their commonly used counterparts, which makes the proposed choppers potential candidates for incorporation in future onboard energy storage systems.

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Dissertation Outline

This dissertation is divided into seven chapters as follows:

- **Chapter 1:** This chapter gives a brief overview of the utilization of onboard energy storage systems in electric railway vehicles, presents the research objectives, and describes the outline of this dissertation.

- **Chapter 2:** This chapter contains a literature review of high-power non-isolated bidirectional choppers used in dc electric railways, where various chopper topologies are presented and discussed.

- **Chapter 3:** This chapter presents the proposed interleaved bidirectional chopper with auxiliary converters, where the circuit configuration, the principles of operation, and the converter control, are discussed in detail. Besides, a comparison with the conventional interleaved chopper is presented and discussed. The operation of the proposed chopper and its control

method are validated by experiments performed on a downscaled prototype.

- **Chapter 4:** This chapter presents the startup procedure that is required for the proposed chopper in chapter 3 to start its operation. Moreover, the operation of the auxiliary converter as a solid-state dc circuit breaker is presented. The converter startup procedure and the circuit breaker operation are experimentally validated by experiments performed on a downscaled prototype.

- **Chapter 5:** This chapter presents a compact high-power non-inverting bidirectional buck-boost chopper for onboard battery energy storage systems, where the proposed chopper topology, the working principles, and the chopper control, are discussed in details. Also, a comparison with the four-switch non-inverting bidirectional buck-boost chopper is presented and discussed. The operation of the proposed chopper and its control method are validated by experiments performed on a downscaled prototype.

- **Chapter 6:** This chapter presents a modified phase-shifted pulse-width modulation (PSPWM) for the cascaded full-bridge cells used in the auxiliary converters. The proposed PSPWM is shown to significantly reduce the peak-to-peak ripple current compared with the conventional PSPWM used in chapter 3. The proposed PSPWM is validated by simulations and experiments performed on a down-scaled prototype.

- **Chapter 7:** This chapter concludes this dissertation and presents some future research

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List of Publications

Journals

- H. J. Ahmad and M. Hagiwara, "Interleaved Bidirectional Chopper With Auxiliary Converters for DC Electric Railways," in IEEE Transactions on Power Electronics, vol. 36, no. 5, pp. 5336-5347, May 2021, doi: 10.1109/TPEL.2020.3031668.

- H. J. Ahmad and M. Hagiwara, "A Compact High-Power Non-Inverting Bidirectional Buck-Boost Chopper for Onboard Battery Energy Storage Systems," in IEEE Transactions on Power Electronics, doi:10.1109/TPEL.2021.3106240.

International Conferences

- H. J. Ahmad, H. Ohnishi and M. Hagiwara, "Start-Up and Transient Operation of a Bidirectional Chopper With an Auxiliary Converter," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), Niigata, 2018, pp. 3273-3279, doi: 10.23919/IPEC.2018.8507570.

- H. J. Ahmad and M. Hagiwara, "Interleaved Bidirectional Chopper With Auxiliary Converters for Battery Energy Storage Systems," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 2090-2097, doi: 10.1109/APEC39645.2020.9124220.

- H. J. Ahmad and M. Hagiwara, "A Non-Isolated Bidirectional Buck-Boost Chopper With Auxiliary Converter for Battery Energy Storage Systems," 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia), Nanjing, China, 2020.

- H. J. Ahmad and M. Hagiwara, "Modified Phase-Shifted PWM for Interleaved Bidirectional Chopper With Auxiliary Converters," 2021 IEEE 12th Energy Conversion Congress and Exposition - Asia (ECCE-Asia), 2021, pp. 755-761, doi: 10.1109/ECCE-Asia49820.2021.9479010.