RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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Doctoral student of program „Computer control of electrical technology”

DEVELOPMENT OF POWER ELECTRIC CONVERTERS FOR HYDROGEN ENERGY EQUIPMENT

Summary of doctoral thesis

Scientific supervisor
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Riga 2011

UDK 662.769.2 + 621.314 (043.2)
St 267 d

Steiks I. Development of power electric converters for hydrogen energy equipment. Summary of doctoral thesis.-R.:RTU, 2011.-17pp.

Printed according to the decision of „RTU P-14" from May the 25th, 2011. Protocol No. 56

This work has been supported by the European Social Fund within the project „Support for the implementation of doctoral studies at Riga Technical University".

ISBN 978-9984-49-347-3

DOCTORATE WORK
PRESENTED TO OBTAIN THE DOCTOR'S DEGREE IN ENGINEERING SCIENCES AT RIGA TECHNICAL UNIVERSITY

Doctorate work for the doctor's degree in the engineering sciences was publicity presented on the 2th of August 2011 in Riga Technical University, Faculty of Power and Electrical Engineering, Kronvalda blv. 1, room 117.

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CONFIRMATION

Hereby I confirm that I have worked out the present doctorate work, which is submitted for consideration to the Riga Technical University for the degree of Doctor of engineering sciences. Doctorate work has not been submitted in any other university for obtaining the Doctor's degree.

Ingars Steiks …………………………….

Date: 19th of July 2011

The doctorate work is written in Latvian language, contains: 146 pages, introduction, 4 chapters, conclusions, 130 figures, 103 references and 7 appendixes.

CONTENTS

SIGNIFICANCE OF THE TOPIC

Significant and required work for the systems of electric power supply, and for the applications of the renewable energy resources. The research and development of the power converters for the fuel cell is being carried around the world and especially in EU. The research and development of power converters for the grid connection and for households' applications is important. The connection of the different power fuel cells is allowed by modular power converters.

OBJECTIVE OF THE WORK AND FULFILLED TASKS

The objective of this thesis is to develop power electric converters for hydrogen energy equipment. Several tasks were defined to fulfill the objective:

- The research and analysis of the specifications, serial and parallel connections of the hydrogen fuel cell;
- Classify the possibilities to deliver the electric power of hydrogen fuel cell to the public grid;
- Research, analyze and develop double inductor push-pull converter, and possibility to avoid overvoltage of the power semiconductor switches.
- Research, analyze and develop modular multilevel cascaded direct-current – alternating-current converter;
- For the control and feedback of the power electric converters for hydrogen energy equipment using field-programmable gate array.

METHODS AND MEANS OF RESEARCH

For the research and analysis of the hydrogen fuel cell characteristics, direct-current – direct-current and multilevel direct-current – alternating current power scheme and control mathematical analysis software Matlab is used.

The algorithms of the control and feedback are implemented in field-programmable gate array (FPGA) Xilinx Spartan 3E by Xilinx ISE Webpack 13.1 software.

The experimental research has been carried out at the laboratory of Institute of Industrial Electronics and Electrical Engineering at the Faculty of Power and Electrical Engineering of Riga Technical University.

SCIENTIFIC ORIGINALITY

The development and experimental verification of the modular hydrogen power converter have been carried out.

The experimental research of serial and parallel connection of fuel cells has been done, and equations of fuel cell's characteristic have been carried out to simulate static operation modes of power converters and fuel cell systems.

An active clamping circuit has been applied for current-fed double inductor push-pull converter to decrease the overshoot of the voltage of main power transistors.

Inventions have been done for hydrogen energy equipment, including: multilevel DC/AC power converter, DC/DC power converter, system with double-layer capacitor and battery, and a power supply with hydrogen's fuel cell.

PRACTICAL APPLICATION OF THE WORK

The elaborated current-fed double inductor push-pull converter with the cascaded multilevel DC/AC converter is appropriated for hydrogen power equipment.

Developed power electric converter system for hydrogen energy equipment will be used for autonomous households and for consumers of industrial voltage. Modularity of developed power electric converter system allows adjusting the system to the number of fuel cell stacks by consumer.

The developed laboratory set-up has provided a possibility to improve the algorithms of the control of the cascaded multilevel DC/AC converter including space vector modulation and fuzzy logic control algorithms with computer control equipment DS1103PPC for electrical technology.

WORK APPROBATION

1. 14th international conference „EPE-PEMC 2010”, Ohrid, Macedonia, 2010
2. 51th scientific conference of Riga Technical University: Power and Electrical Engineering, Riga, Latvia, 2010
3. 9th international symposium „Topical Problems in the Field of Electrical and Power Engineering 2010”, Parnu, Estonia, 2010
4. 8th international symposium „Topical Problems in the Field of Electrical and Power Engineering 2010”, Parnu, Estonia, 2010
5. 13th European conference on Power Electronics and Applications „EPE 2009”, Barcelona, Spain, 2009
6. 50th scientific conference of Riga Technical University: Power and Electrical Engineering, Riga, Latvia, 2009
7. 5th international symposium „Topical Problems in the Field of Electrical and Power Engineering 2010”, Kuressaare, Estonia, 2008
8. 4th international symposium „Topical Problems in the Field of Electrical and Power Engineering 2010”, Kuressaare, Estonia, 2007
9. The IEEE Industry Applications Society Workshop, Renewable Energy Based Units and Systems, St. Petersburg, Russia, 2006
10. 3th international symposium „Topical Problems in the Field of Electrical and Power Engineering 2010”, Kuressaare, Estonia, 2006

AUTHOR’S PUBLICATIONS

1. A.Andreiciks, I.Steiks, O.Krievs and L.Ribickis „Current-fed DC/DC converter for fuel cell applications”, EPE-PEMC 2010,Ohrid, Macedonia, 2010, ISBN 978-1-4244-7854-5 (IEEE datubāze)
2. I.Steiks, L.Ribickis „Capacitor divider voltage monitoring by using Field-Programmable Gate Array (FPGA)”, EPE-PEMC 2010, Ohrid, Macedonia, 2010, ISSN 978-1-4244-7854-5 (IEEE datubāze)
3. A.Andreiciks, I.Steiks and O.Krievs „Current-fed Step-up DC/DC converter for Fuel Cell Applications with active Overvoltage Clamping”, Scientific Journal of Riga Technical University: Power and Electrical Engineering, Riga, Latvia Volume 27, 2010, ISSN 1407-7345
4. O.Krievs, I.Steiks and L.Ribickis „A PLL Scheme for Synchronization with Grid Voltage Phasor in Active Power Filter Systems”, Scientific Journal of Riga Technical

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5. I.Steiks, O.Krievs and L.Ribickis „A PLL for Estimation of the Voltage Vector Position in a Parallel Active Filter System", 8th International Symposium Topical Problems in the Field of Electrical and Power Engineering, Parnu, Estonia, 2010, ISBN 978-9985-69-049-9
6. A.Andreiciks, I.Steiks, L.Ribickis „An active clamping current-fed double inductor push-pull converter with current control model for fuel cell applications", 9th International Symposium Topical Problems in the Field of Electrical and Power Engineering, Parnu, Estonia, 2010, ISBN 978-9985-9089-3-8
7. A.Purvins, O.Krievs, I.Steiks and L.Ribickis „Influence of the Current Ripple on the Hydrogen Fuel Cell Powered Inverter System Efficiency", EPE 2009, Barcelona, Spain, 2009, ISBN 9789075815009 (EPE datubāze)
8. A.Andreiciks, K.Vitols, O.Krievs, I.Steiks „Current Fed Step-up DC/DC converter for fuel cell inverter applications", Scientific Journal of Riga Technical University: Power and Electrical Engineering, Riga, Latvia, Volume 25, 2009, ISSN 1407-7345
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10. I.Steiks, A.Purvins, O.Krievs, L.Ribickis, J.Greivulis „Modelling of a high efficiency DC/DC converter for the PEM fuel cell system", 5th International Symposium Topical Problems in the Field of Electrical and Power Engineering, Kuressaare, Estonia, 2008, ISBN 978-9985-69-046-8
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INVENTIONS

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4. A.Purvins, J.Greivulis, I.Steiks, O.Krievs, L.Ribickis „Power supply with hydrogen's fuel cell", Patent Office of the Republic of Latvia, 20.11.2008., Nr. LV 13774 B

CONTENTS OF THE DOCTORAL THESIS

INTRODUCTION

Every year the hydrogen power industry has been increasingly integrated in different type of vehicles, power supply of autonomous households and back-up power supplies. The research of the alternative for the fossil energy resources stimulates swift growth of the hydrogen energetics. This thesis is devoted to development of power electric converters for the hydrogen energy equipment, as the research and development of the power converters for the fuel cell is being carried around the world and especially in EU.

Development of power electric converters for the hydrogen energy equipment could be divided in to two parts: one of them consists of the analysis and research of hydrogen energy equipment, and the second part consists of the research of power converters.

For the autonomous power supply or for the grid applications the output voltage of the hydrogen fuel cells is relatively low. One of the solutions to avoid this problem is to connect fuel cell in series, but, in the case of parallel connection, more power at the same voltage level can be carried out.

It is possible to increase or to decrease low and variable output voltage of the fuel cell by using power electronic converters. Increasing the voltage is more rational solution in order to decrease the active losses created by current. For the multiple voltages increasing transformers are being used, at the same time providing galvanic isolation of input and output. The galvanic isolation between the hydrogen power equipment and the high voltage provides additional protection for the hydrogen power equipment.

Increased voltage levels are rarely used in household applications, therefore creating a necessity for the direct-current/alternating-current power converter.

Another problem of power converters is commutation process of high current with high frequencies that cause overvoltage on semiconductor devices and are source of electromagnetic interference. The usage of an active clamping circuit is recommended to decrease the overvoltage on semiconductor devices of direct-current step-up converter. Whereas, the usage of the multilevel direct-current / alternating-current power converter divides the output voltage multiple voltage levels, therefore decreasing the increase of the voltage and the current during period of time.

The objective of this thesis is to develop power electric converters for hydrogen energy equipment, and to fulfill the objective following tasks are defined. First of all, to carry out the research and analysis of the hydrogen power equipment this also includes its simulation results, and the research and analysis of serial and parallel connection.

Secondly, to carry out the development and research of power electric converters for the hydrogen energy equipment, this also includes development/research of suitable direct-current / direct-current step-up converter and suitable multilevel direct-current / alternating-current topologies and control circuit.

1. THE RESEARCH AND ANALYSIS OF THE FUEL CELL'S SYSTEM

Distribution of the first chapter is represented by Fig.1

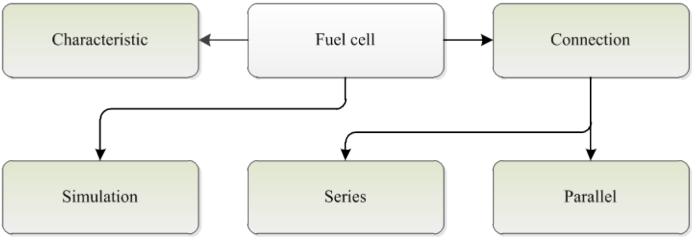

Fig.1. Distribution of the first chapter is represented

During the last twenty years, the increasing price of the fossil resources (Fig.2.) has stimulated the usage of alternative power supply technologies, e.g., the usage of fuel cell to obtain electric and thermal energy. One of the advantages of the fuel cell is their available power range starting form few watts up to megawatts, and also their integration in autonomous power supply.

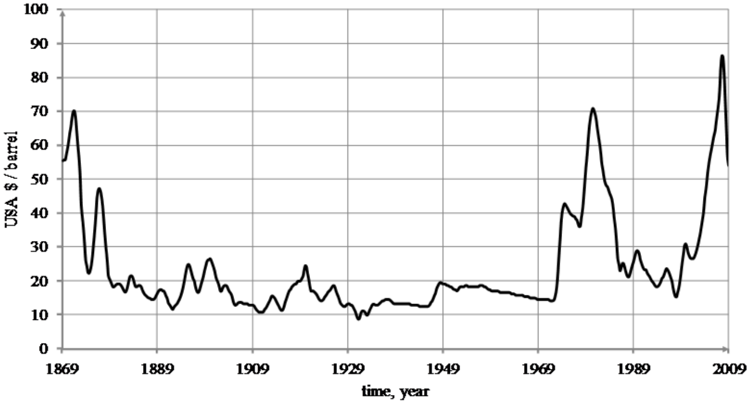

Fig.2. Changes of the crude oil prices from 1869 till 2009

The classical power converter topologies could be applied in order to use fuel cells. The Volt-Ampere (VA) characteristic of the fuel cell represents necessity to adopt control of the power converter, e.g., the output voltage of the fuel cell at no load operation is 50 V, but increasing the load current – the output voltage decreases up to 26V. One of disadvantages of the fuel cell is their inertial electrochemical process compared to capacitors and batteries at swift load changes. Development of analytical model of the fuel cell is useful in order to analytically and practically develop power converters, and to improve precision of the control. By obtaining the experimental data of fuel cell's VA characteristic and by using polynomial approximation it is possible to develop analytical VA characteristic of fuel cell.

Analytical VA characteristic can be used for the control program of the power converter and also for the mathematical software. Polynomial approximation of fuel cell VA:

- Series connected fuel cell module 2:

$$P_{DE2\_vir} = -0{,}185i^2 + 37{,}133i + 15{,}67\ , \qquad (1.)$$

- Series connected fuel cell module 1:

$$P_{DE1\_vir} = -0{,}1962i^2 + 35{,}829i + 19{,}03\ , \qquad (2.)$$

- Parallel connected fuel cell module 2:

$$P_{DE2\_par} = -0{,}1979i^2 + 38{,}171i + 10{,}528\ , \qquad (3.)$$

- Parallel connected fuel cell module 1:

$$P_{DE1\_par} = -0{,}2235i^2 + 37{,}745i + 9{,}9914\ . \qquad (4.)$$

In the cases of the series and parallel connections of the fuel cell it is important to consider the fact, that when increasing the load the necessity of power balances possibilities occurs. At the nominal load power of the fuel cell in series connection load difference is 7.9%, but in case of parallel connection - 13.7%. In case of the series connection the load current difference is 0.9%, but the difference of the output voltage of fuel cell is 7.1%. In case of parallel connection the difference of load voltage is 0.7%, but the load current differs by 13%. The difference of temperature of fuel cell modules at series connection is 4.9%, but in case of parallel connection – 0.6% at nominal load of fuel cell. The main reason of unequal load balance between fuel cells is their inertial electrochemical process, and the age of fuel cell. Laboratory set-up for fuel cell investigations is depictured by Fig.3.

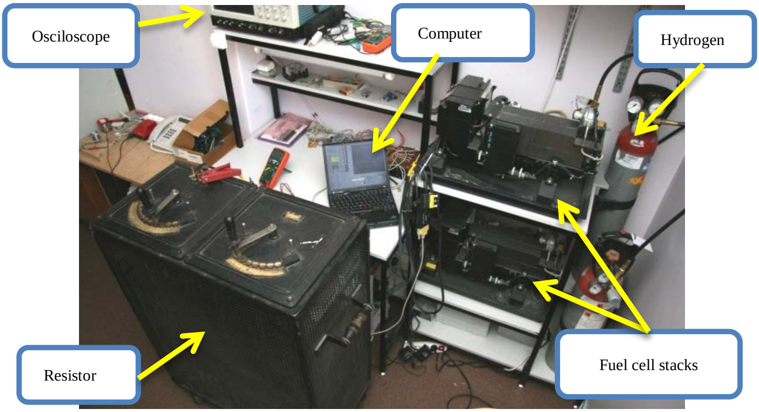

Fig.3. Laboratory set-up of fuel cell modules

2. THE ANALYSIS AND CLASSIFICATION OF POWER CONVERTERS FOR THE EQUIPMENT OF THE FUEL CELL

The delivery of the electric power to the grid obtained during the electrochemical process of the fuel cell may serve as back-up power supply system or, e.g., supply autonomous household with electric power. To deliver the electric power to the grid it is recommended to use high-frequency inverter with current feedback.

Comparing three topologies of direct-current high-frequency power converters, current-fed double inductor push-pull converter is considered to be the most appropriate

(Fig. 4.). This kind of topology allows decreasing the ripple of the input current and also eliminates divided primary winding of transformer. The electrical process is depictured by Fig.5.

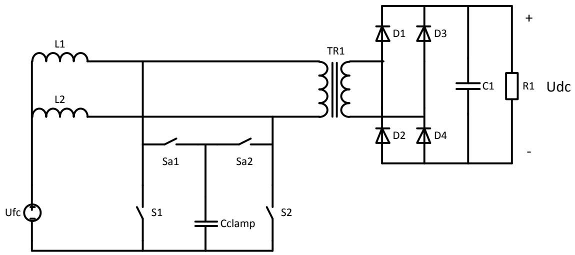

Fig.4. Current-fed double inductor push-pull converter with active clamping

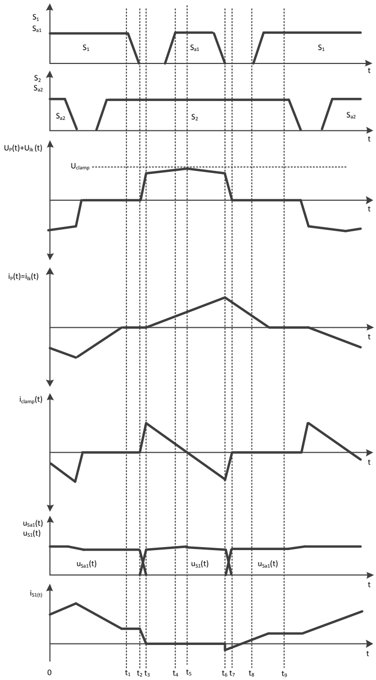

Fig.5. Active clamping circuit rules

By caring out the analysis of the topologies of multilevel inverters, the cascaded modular multilevel converter (Fig. 6.) has been chosen as most suitable; because of the requirement for the isolated power supply is fulfilled by fuel cells. In the case of the cascaded modular multilevel converter the number of used component is a ~1.4 time smaller in the case of flying capacitor topology and ~1.8 time smaller in the case of neutral point clamped topology converter.

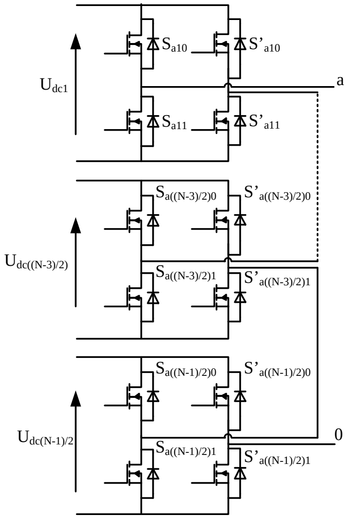

Fig. 6.att. the cascaded modular multilevel converter

3. THE SIMULATION OF TOPOLOGIES AND CONTROL FOR THE SYSTEM OF POWER CONVERTERS

In this chapter an active clamping current-fed double inductor push-pull converter analytical model is created in Matlbab/Simulink; possible switch state combinations are also provided. This chapter also includes the cascaded modular multilevel converter with appropriate output voltage waveform diagram and possible switch state combination's table is also provided. It has been noticed that changes of THD is within range of ±1% in the case of multiple carrier signal level-shifted topologies. If the frequency of carrier signal has been increased or decreased, the THD remains in the range of ±1%.

This chapter also includes the control algorithm of an active clamping current-fed double inductor push-pull converter written in VHDL language. There is realized output voltage feedback also.

The control of the cascaded modular multilevel converter is represented in VHDL language. The load varies after each period of output waveform to balance it over modules.

4. THE EXPERIMENTAL RESEARCH OF THE POWER CONVERTER FOR THE SYSTEM OF THE FUEL CELL

This chapter includes experiments of power electric converter for hydrogen energy equipment (functional scheme by Fig.7.) and they are separated in three parts.

First of all, an active clamping current-fed double inductor push-pull converter prototype has been build and control of converters is implemented in FGPA hardware. An experimental verification has been done (laboratory set-up by Fig.8.)

Secondly, 7-level cascaded modular multilevel converter has been built and power balance algorithm implemented in FPGA hardware. Experimental results approve appropriate working conditions.

Third, galvanic isolated voltage measurement circuit has been developed with auxiliary direct-current / direct-current converter. There also is realized control algorithm to measure the frequency of the square-waveform signal and its implementation in FGPA has been verified.

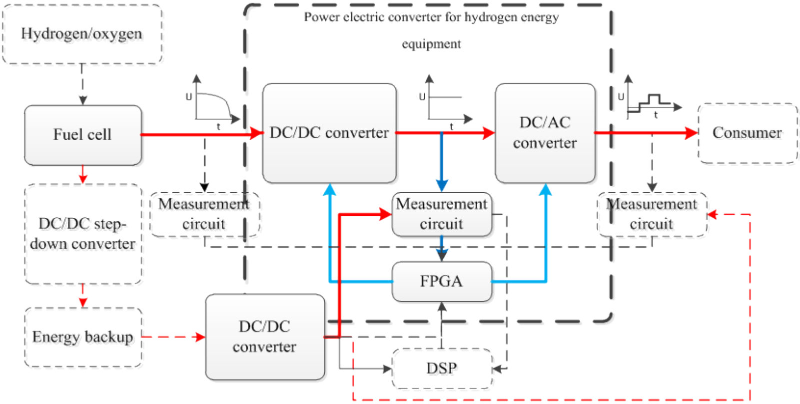

Fig.7. Functional scheme of power electric converter for hydrogen energy equipment

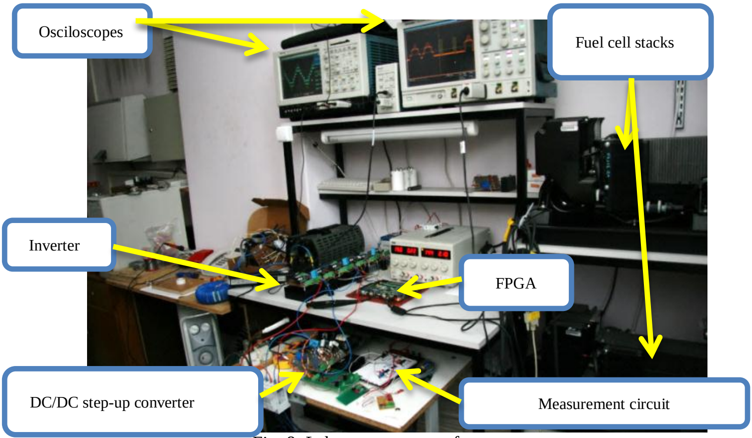

Fig. 8. Laboratory set-up of converters

CONCLUSIONS

Hydrogen power is a promising alternative to the growing usage of the fossil energy resources and to the increasing prices of non-renewable resources. Although the usage of the fuel cell for electric vehicle may be considered as a trend, its rational to use it for back-up, and household application and to electrify industrial buildings. Development and research of power electric converters for hydrogen energy equipment has been done including step-up direct-current / direct-current power converter and cascaded modular multilevel converter development and research.

The experimental research of the fuel cell module has been done, proving, that the VA characteristic creates hysteresis, therefore approving its inertia of electrochemical process, what is a disadvantage of the fuel cell. By obtaining the experimental data of fuel cell's VA characteristic and by using polynomial approximation it is possible to develop analytical VA characteristic of fuel cell. Analytical VA characteristic can be used for the development of the power converters.

As novelty the series and parallel connections of the fuel cell experimental investigation has been done. It is important to consider the fact, that when increasing the load the necessity of power balances possibilities occurs. At the nominal load power of the fuel cell in series connection load difference is 7.9%, but in case of parallel connection - 13.7%.

Compared topologies of direct-current high-frequency power converters, current-fed double inductor push-pull converter is considered to be the most appropriate in this thesis. This kind of topology allows decreasing the ripple of the input current and also eliminates divided primary winding of the transformer. To avoid the overvoltage of the power semiconductor switches, an active clamping circuit with two semiconductor switches and a capacitor has been applied.

By caring out the analysis of the topologies of multilevel inverters, the cascaded modular multilevel converter has been chosen as most suitable for this particular case; because of the requirement for the isolated power supply is fulfilled by fuel cells. It also uses fewer components compared to neutral point clamped topology converter (~1.8 times).

The simulation results of the cascaded modular multilevel converter prove that the THD remains in the range of ±1% in the case of changing frequency of carrier signal.

The unbalanced load between the cascaded modular multilevel converter modules has been avoided by adding appropriate control algorithm sequence.

The prototype of the power electric converter for hydrogen energy equipment has been developed, consisting of: an active clamping current-fed double inductor push-pull converter; the cascaded modular multilevel converter and voltage measuring circuit with appropriate auxiliary power supply. The control of the power electric converter for hydrogen energy equipment has been realized by FPGA hardware.

The development of power electric converters for the hydrogen energy equipment is still the one of the state-of-art topics. That is proven by, first, thesis approbation in international conferences [6]-[9],[95],[96], secondly, author's publications [76], [77], [79], [80], [94] and thirdly, author's inventions registered at Patent Office of the Republic of Latvia:

- Multilevel direct-current – alternating current power converter with fuel cell of the hydrogen [73];
- Direct-current - direct-current power converter with fuel cell of hydrogen [75];
- The system of hydrogen's fuel cell with double-layer capacitor and battery [74];
- Power supply with hydrogen's fuel cell [78].

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Ingars STEIKS

Development of power electric converters for hydrogen energy equipment

Summary of doctoral thesis

Calculation 20 copies.
Printed and bound at the RTU, 1 Kronvalda blv.,
Riga LV- 1010, Latvia