

UDC 621.314

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Novel family of voltage converters with low harmonic distortion using coupled reactors

This paper presented a novel approach to the multipulse voltage converters (VC), especially voltage source inverters (VSI) and matrix converters (MC) based on several typical identical modules connected in parallel using Inductive Current Splitters/Mergers. Such arrangements resulting in lower voltage distortions at extremely low switching frequency. Proposed new arrangements was validated by simulation. Laboratory models of 18- and 24-pulse 3-level VSI arrangements was also investigated experimentally. Results of simulation and laboratory tests of experimental models are presented in the paper.

References 15, figures 10, tables 1.

Keywords: multipulse voltage converters; matrix converters coupled inductors; inductive current splitte/merger.

1. Introduction

Two crucial parameters of currently build high power VC arrangements are the efficiency and the generated waveforms distortion level. Both those parameters rely deeply on switching frequency, but unfortunately the relation is opposite. For high switching frequencies inverters generate less

distortions (from power quality and electromagnetic immunity perspective) but they have higher losses. Therefore, one needs to seek for a tradeoff which would allow to achieve satisfactory results.

In [1-4] discuss many different solutions of high power VC. One of the most important aspects of this application is a high efficiency which allows to fully utilize power elements and simplify the cooling system. The following important problems connected with design of high power converters are: the ability for system to extend by its modularity and low EMI distributions level. To achieve a high efficiency at a low switching frequency and to maintain a good power quality multipulse converters were introduced [5,6]. These branch of VCs use the parallel operation of identical converter topologies which were typically connected by means of a multi-winding transformer providing the converters with phase shifted voltages. This allows the system generate increased number of voltage vectors compering to less complexed converters. The required rotating voltage vector can be more accurately discretized by the converter when the number of pulses is high (Fig. 1).

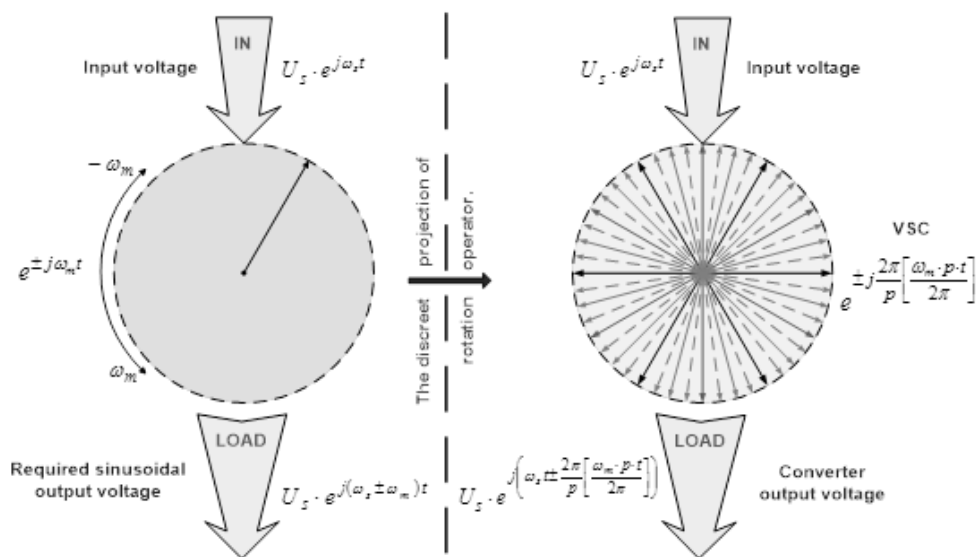


Fig. 1. Principle of operation of multipulse VC's

The multi-winding transformer has to be rated for the full power of the converter. Thus, it tends to be large and adds significant cost to the converter construction. The use of the coupled inductors instead of the transformer allows to phase shift voltages and to reduce the converter dimensions. The literature provides multiple examples of the coupled inductors use for the multiphase system design. The first group of the converters (which were tested with the use of coupled inductors used for multiphase system design) are the diode based rectifiers. This type of converters benefited from having lower input waveforms distortions [7-10]. Similar advantages are if the proposed coupled inductors structures are applied to DC/AC converters using two level VSI [11].

The paper discusses the method of design and synthesis of a new arrangements of a multipulse VC's, especially multilevel VSI and MC. These VC's are built as modules connected in parallel by means of integrated coupled reactors [12,13]. The results of theoretical, simulation and experimental investigations are presented

2. Proposed multipulse VC

The overall arrangements of the proposed multipulse VC is presented on Fig. 2a. The converter

has higher number of the possible voltage vectors which can be applied [14]. The higher number of the VC modules allows to extend the number of voltage vectors which can be applied to the converter output [15]. Further increase of the voltage vector number can be achieved also by paralleling and phase shifting converters. Therefore, a investigated VC's was proposed which are based on multilevel VSI and MC modules and are connected in parallel by means of coupled reactors to achieve high number of output vectors. Two general configurations of the coupled reactors were tested in the interest of this paper. First is current merging connection CM(λ) of single phase inductors presented in Fig. 2b and phase shifting inductors PS(λ) set given in Fig. 2c. The required phase shift of the VC modules can be applied by means of the winding turn ratio recalculation. To calculate required turn ratio for given angle λ one should use equation (1a) for CM(λ) element and (1b) for PS(λ) element:

$$\begin{aligned}
 &a) \quad N_D/N_C = 2 \cos \lambda, \\
 &b) \quad N_A/N_B = \frac{\sin(2\pi/p_n - \lambda)}{\sin \lambda}, \quad (1) \\
 &\quad N_\Sigma = N_A + N_B.
 \end{aligned}$$

where: p_n – is number of pulses of the proposed modular VC.

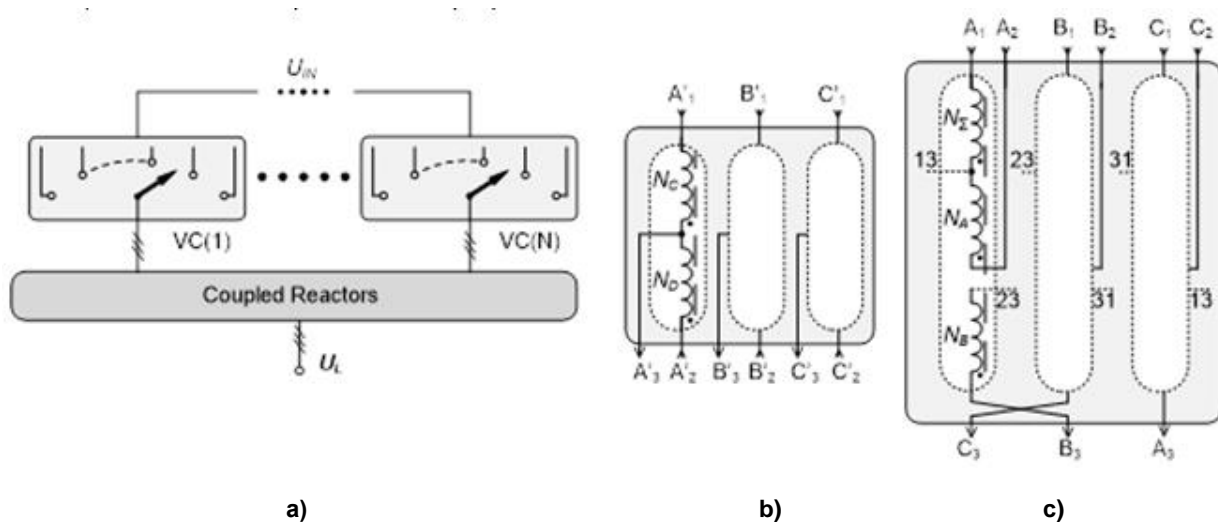


Fig. 2. The overall topology of the proposed multipulse VC (a), and current merger CM(λ) (b) m and phase shifting PS(λ) (c) coupled reactors

A. Multipulse VSI arrangements

Fig. 3 presented basic arrangements of the multi-pulse inverters. Used 2- or more levels of the 6-pulse VSI modules are identical. Fig. 4 shows output voltage for different proposed VSI arrange-

ments operating at output frequency and switching frequency equal to 50 Hz. The THD voltage coefficient calculated for the tested inverters structures are given in Table 1. One can notice that the increase of voltage levels and pulses can significantly reduce the voltage distortion. These simulation results were obtained for the simplified control

scheme which was not equipped with the output parameters feedback. Nonetheless, it is possible to arrange full control system structure if e.g. nonline-

ar receivers will be supplied from the converter and high power quality is required.

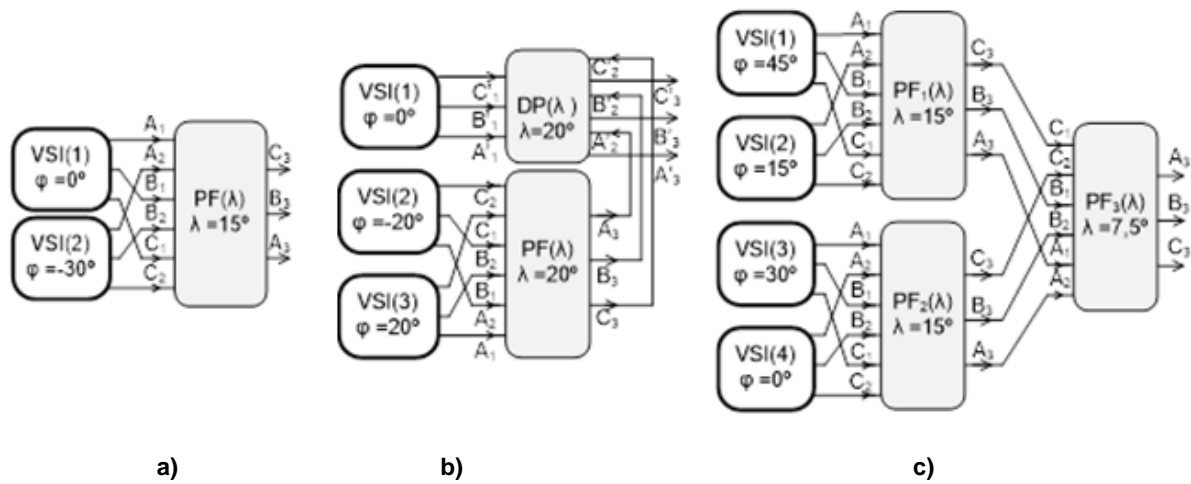


Fig. 3. Structures of connections of 6-pulse VSI modules: 12-pulse VSI arrangement (a), 18-pulse VSI arrangement (b), 24-pulse VSI arrangement (c)

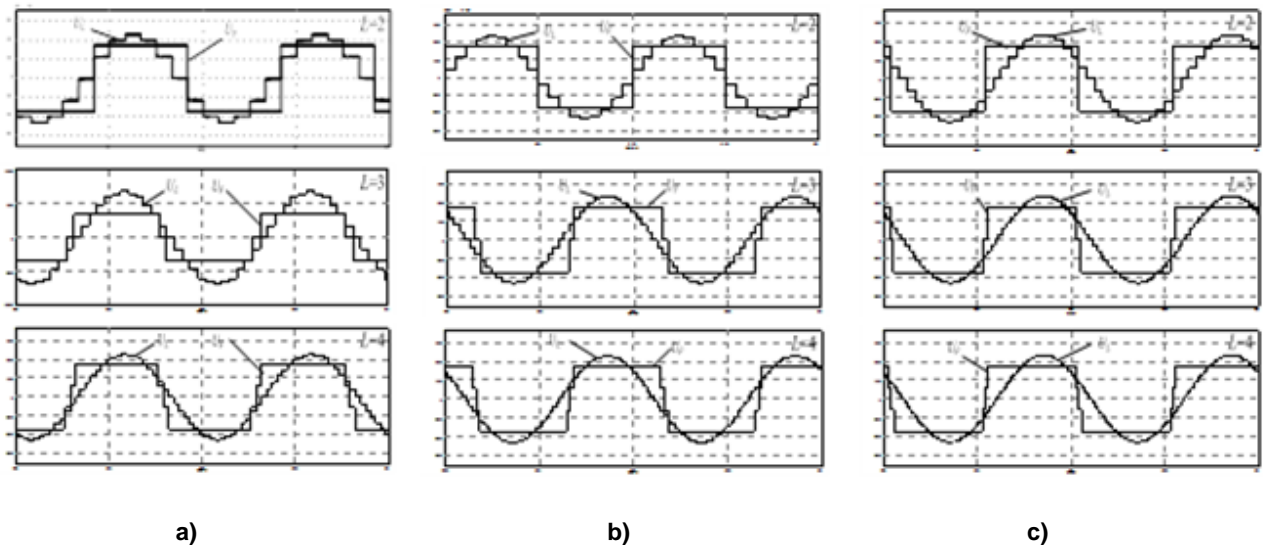


Fig. 4. Output voltage U_L and inverter phase voltage U_L for proposed multi-pulse VC arrangements operation of 2-, 3- and 4- level VSI modules in: 12-pulse structure (a), 18-pulse structure (b), 24-pulse structure (c)

Table 1. Theoretical value of THD output voltage coefficients of tested the multi-pulse inverter structures

Number levels (L) of the VSI modules	Connection type of the VSI modules			
	6-pulse	12-pulse	18-pulse	24-pulse
2	31,1%	14,7%	9,7%	7,4%
3	16,9%	7,4%	4,9%	3,7%
4	11,8%	5,0%	3,3%	2,5%
5	9,39%	3,83%	2,48%	1,79%

B. Multipulse MC arrangements

The proposed multi-pulse MC structures are based on a standard 3-pulse MC modules depicted for example in [2, 3]. Two reactors arrangements from Fig. 2 a possibility to build the wide range of arrangements of the multipulse MC. Three examples of such systems are given in Fig. 5 presenting 6-pulse, 9-pulse and 12-pulse systems accordingly. Detailed 9-pulse MC arrangements presented in Fig. 6. In this configuration both $CM(\lambda)$ and $PS(\lambda)$ reactors structures were used.

The invented multi-pulse MC topologies were validated with the use of PSIM v.10 software simulation models. The nonlinearities of the

components were neglected in the simulations. The load was simulated as series connection of a resistor and inductor with $\cos(\varphi)=0,96$. Also, in Fig. 6 voltage and current waveforms for negative sequence scheme modulated obtained from accordingly typical 3-pulse and 6-pulse, 9-pulse and 12-pulse arrangements of MC were presented. VSA VSB and VSC are input voltage waveforms. ISA is one of input phase currents. On the other hand VLA, VLB, VLC and ILA are the corresponding output parameters. For clarity current waveforms were multiplied by 10. One might notice that the observed distortion level in the input and output current, but also in the output voltage significantly drops with the number of pulses.

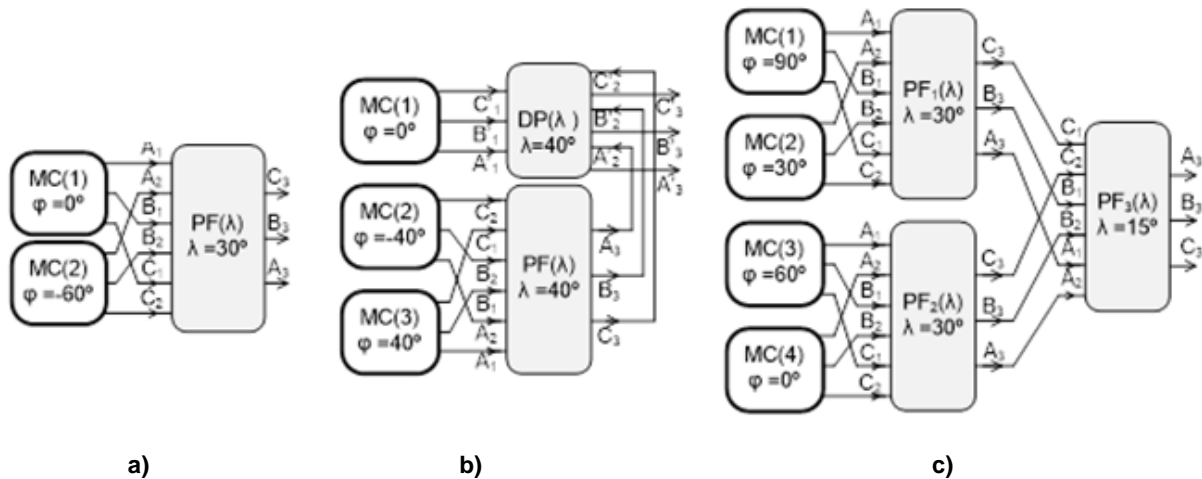


Fig. 5. Structures of connections of 3-pulse MC modules: 6-pulse MC arrangement (a), 9-pulse MC arrangement (b), 12-pulse MC arrangement (c)

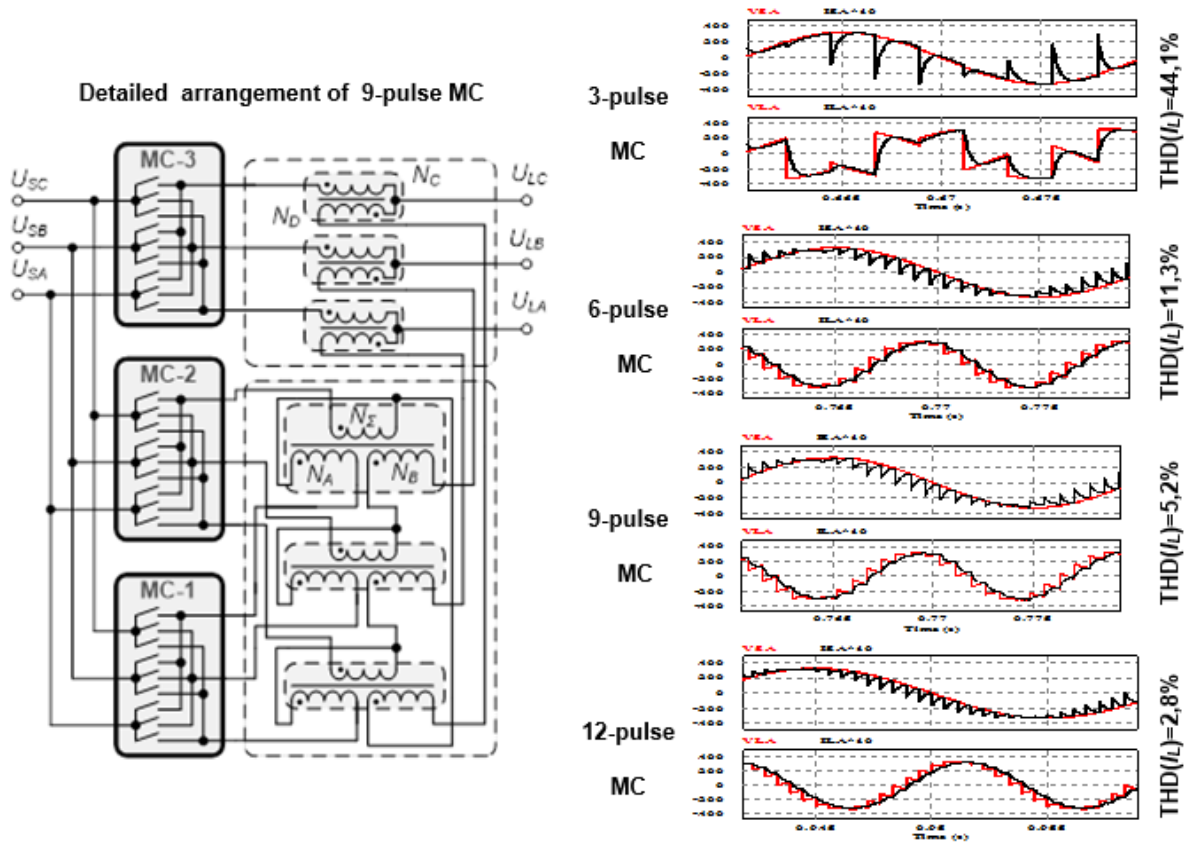


Fig. 6. Example of 9-pulse MC arrangement as well as current and voltage waveforms observed in different multipulse MC arrangements

2. Experimental results

Based on analyses it was decided to test 18-pulse and 24-pulse NPC VSI arrangements. In the experimental investigated each paralleled VSI module has to be phase shifted by 20° or 15°

respectively. Fig. 7 presented the laboratory model of 18-pulse NPC VSI arrangement. The model contains three identical NPC VSI, control board, and the set of the coupled inductors. The model is rated for 15 kW/400V.

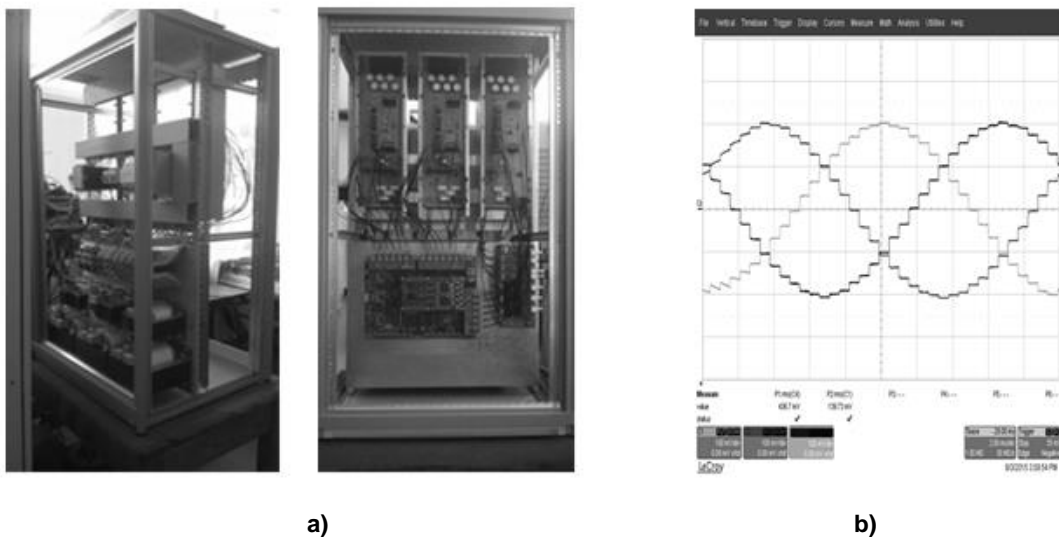


Fig. 7. View of laboratory setup of the 15kW 18-pulse NPC VSI model (a) and output phase current in the case of symmetrical R load (b)

As a first experiment, the quality of the voltage waveform generation was tested (Fig. 8). It can be seen that the THD measured has the value below 5% in the wide range of the output load. The extremely low switching frequency used in the proposed converter allowed to achieve high efficiency of the energy conversion. The efficiency curve as the function of output power is presented also in Fig. 8. The converter was tested with the use 6-pulse diode rectifier.

Fig. 9a presents the waveforms of output voltage and currents observed during the efficiency

test. It can be seen that the converter output voltage is not affected by the highly distorted current. This is observed, in that the equivalent impedance of the converter is low, due to the lack of the standard filter. The low equivalent impedance brings another feature to the device. It can easily supply unbalanced load. Such operation was also tested and proved that the converter voltage balance is not influenced by the non-symmetrical load. In addition Fig. 9b presents waveforms obtained while the converter was tested under resistive-inductive load.

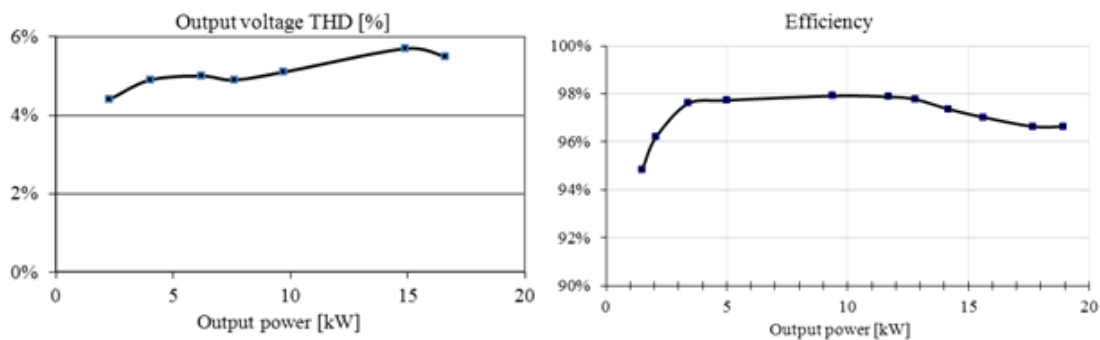


Fig. 8. Output voltage distortion and efficiency of the 18-pulse NPC VSI laboratory model

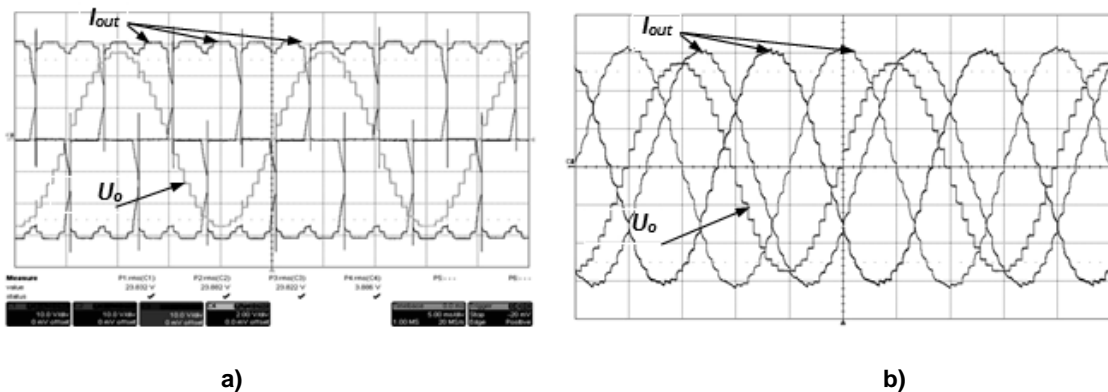


Fig. 9. Typical output voltage and currents during test of 18-pulse NPC VSI model: rectifier (a) and RL (b) load

Additionally, figure 10 shows the voltage and current oscillograms for the above presented 18-pulse and newly developed 24-pulse VSI arrangements. As you can see, the increase in the

number of pulses significantly improves the quality of the output waveform. It is important at this high accuracy performance coupled reactors.

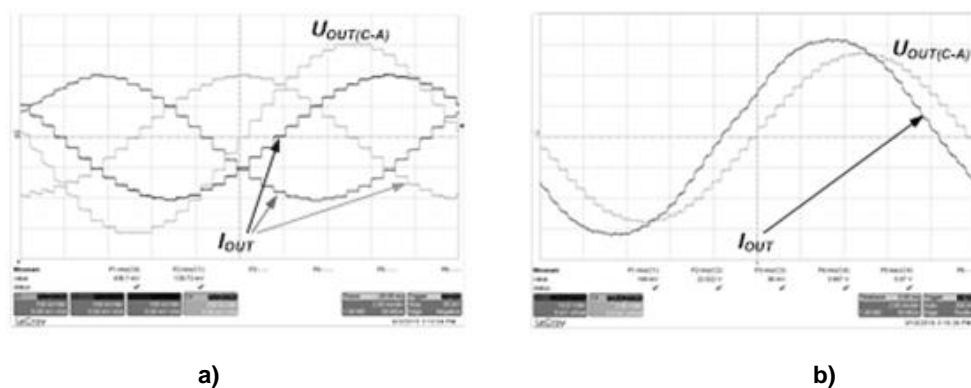


Fig.10. Oscillograms of output voltages and currents for 18-pulse (a) and 24-pulse (a) NPC VSI arrangements

3. Conclusion

The result presented in this article suggest that the multi-pulse VC arrangements based on VSI or MC modules connected in parallel by means coupled reactors, is a very promising technology for high power converters. The high power equality and the high efficiency are the advantages of the proposed technology. The proposed VC structures are fulfilling the conditions of the modular scalable technology

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Поступила в редакцию 29 июля 2016 г.

УДК 621.314

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Новое семейство преобразователей напряжения с низким уровнем гармонических искажений с использованием соединенных индуктивностей

В данной статье представлен новый подход к многоимпульсным преобразователям напряжения, в том числе инверторам напряжения и матричным преобразователям на основе нескольких типовых идентичных модулей, соединенных параллельно с использованием Inductive Current Splitters / Mergers. Такие механизмы приводят к снижению напряжения искажения при низкой частоте переключения. Предлагаемые новые механизмы были подтверждены с помощью моделирования. Лабораторные модели 18- и 24-импульсных 3-уровневый преобразователей напряжения были также исследованы экспериментально. Результаты моделирования и лабораторных испытаний экспериментальных моделей представлены в работе. Библиография: 15, рис. 10, табл. 1.

Ключевые слова: многоимпульсные преобразователи напряжения; матричные преобразователи; катушки индуктивности; гармонические искажения.

УДК 621.314

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Нове сімейство перетворювачів напруги з низьким рівнем гармонічних спотворень з використанням з'єднаних індуктивностей

У даній статті представлений новий підхід до багатоімпульсних перетворювачів напруги, зокрема інверторів напруги і матричних перетворювачів на основі кількох типових ідентичних модулів, з'єднаних паралельно з використанням Inductive Current Splitters/Mergers. Такі механізми призводять до зниження напруги спотворення при низькій частоті перемикання. Пропоновані нові механізми була підтвержені за допомогою моделювання. Лабораторні моделі 18- і 24-імпульсних 3-рівневих перетворювачів напруги були також досліджені експериментально. Результати моделювання і лабораторних випробувань експериментальних моделей представлені в роботі. Бібліографія: 15, рис. 10, табл. 1.

Ключові слова: багатоімпульсні перетворювачі напруги; матричні перетворювачі; котушки індуктивності; гармонічні спотворення.

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