UDC 621.314.58

THD Reduction of Inverters in Photovoltaic Power Systems

DOI: 10.20535/2523-4455.mea.207543

I. S. Fedin[f], ORCID 0000-0003-0264-5067
T. O. Tereshchenko[s], Dr.Sc.(Eng.) Prof., ORCID 0000-0003-4009-2854
J. S. Yamnenko[s], Dr.Sc.(Eng.) Prof., ORCID 0000-0002-9796-6420
Department of electronic devices and systems
National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, ROR 00syn5v21
Kiev, Ukraine

Abstract—**Photovoltaic power systems are quite common in modern consumer power systems. Alongside the power sources, converters for photovoltaic energy systems made their own evolution path that was defined by two main requirements that have to be fulfilled: maximization of the power source usage and provision of the output voltage THD ratio on the levels defined by international standards. In modern power systems z-/quasi-z- source inverters are commonly used due to their ability to maintain system operation in maximum power point of the solar panel without the implementation of the additional devices. THD ratios of these topologies exceed the limits defined by international standards therefore they have to be reduced. This article is devoted to determination, comparison, and discussion of THD reduction methods for the PV power system’s inverters. In the practical part of the article three inverter topologies, quasi-z-source, three-level cascaded quasi-z-source and three-level cascaded inverter in which output cell’s voltages are defined by the desirable output voltage decomposition result achieved by the orthogonal transformation were developed and simulated in Simulink modeling environment as the models that represent different approaches on THD ratio reduction. As a result of simulation output voltages waveform, their spectra, and THD ratio for each model were obtained. According to them, three-level cascaded z-source inverter which output cell’s voltages are defined by the desirable output voltage decomposition results achieved by the orthogonal transformation could provide the lowest THD ratio among considered devices. In conclusion to the study based on the advantages and drawbacks of each THD reduction method, outlined in the discussion section, the combination of cascaded multilevel topology implementation with size-reduced passive output filter was chosen as a solution that will simultaneously allow to achieve proper values of THD ratio, reduce the size of an output filter and avoid excessive sophistication of inverter’s control system. As potentially perspective fields of research were defined modernization of control algorithms, stabilization of the multilevel inverters cell’s output voltage of and further research of the methods that are based on the mathematical determination of the cell’s output voltage and their implementation possibility in cascaded multilevel z-/quasi-z-topologies. This could result in their wider implementation and popularization in future converter devices that might lead to the future complete elimination of the passive filters from the upcoming schematics due to the lack of the additional output voltage filtering necessity.**

Key words — z-source inverters; renewable power systems; cascaded multilevel inverters; THD ratio, output voltage quality.

I. INTRODUCTION

Photovoltaic power sources are quite common in modern renewable power systems. They are used separately or in combination with other sources of renewable energy. They generate DC voltage that has to be transformed into AC voltage that is typical for most consumer power networks. To solve this task every renewable power system that has photovoltaic energy source and fed its output voltage to the consumer power network include inverter as a DC/AC voltage converter (Fig.1) [1][2][3].

According to the numerous studies, the main goal of the voltage inverter for the photovoltaic system is an increase of efficiency and reduction of output voltage’s THD ratio to achieve maximum power source utilization via reduction of both transformation and filtering losses of the input energy. The evolution of voltage inverters for photovoltaic energy systems outlined two main requirements to the inverters that could significantly increase source utilization: possibility to provide the operation of the inverter in the maximum power point (MPP) of the solar panel and ability to increase the output voltage of the solar panel in the undesired weather conditions (such as low solar radiation level)[4][5][6][7]. These requirements could be fulfilled either through the addition of the supplementary boost converter in the input circuit of a standard full bridge inverter, as it was conducted in the study “Evaluation of the main MPPT techniques for photovoltaic applications” [8], or implementation of the z-source/quasi-z-source inverter topology that was proposed by F.Z Peng in his fundamental study “Z-source inverter” (Fig.2) [9]. The latter development solution resolves this task without inclusion of additional power switch that leads to noise and power loss reduction making it preferable design strategy.

Fig. 1 Typical photovoltaic power system structure

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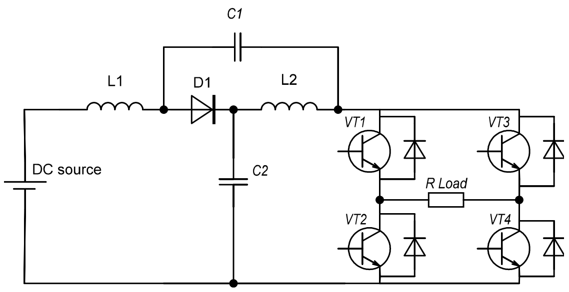


Fig. 2 Quasi-z-source inverter topology

This advantage is provided by both implementation of the unique input impedance circuit and power switch operation state that is called the "shoot-trough" state. The complete operation cycle of the z-source inverter could be separated into three main periods that depend on the power switches operation modes (Fig.3). In the first period, switches are conducted in one of two possible standard operation modes providing the input voltage to the load. Simultaneously this voltage charges capacitors of the impedance circuit.

During the following "shoot-through" state all of the switches remain enabled that leads to energy transmission from capacitors to the inductors of the impedance circuit. Then the energy stored in the inductors during the next standard operation mode added up to the energy of the input power source due to the self-induction EMF phenomena thus providing an increase of the inverter's output voltage [10][11][12][13][14].

Theory of z- and quasi-z-source inverter operation is primarily the same, excepting capacitor and inductor current flow direction in "shoot-through" state for quasi-z-source topology that allows reduction of the capacitor's size and voltage parameters [11][12].

The main disadvantage of the considered operation algorithm is that inclusion of the additional switching mode that implies disconnection of the load results in malformation of the output voltage waveform. This results in output voltage THD ratio increase hence additional filtering losses. That develops the problem of z-/quasi-z-source inverter THD ratio reduction.

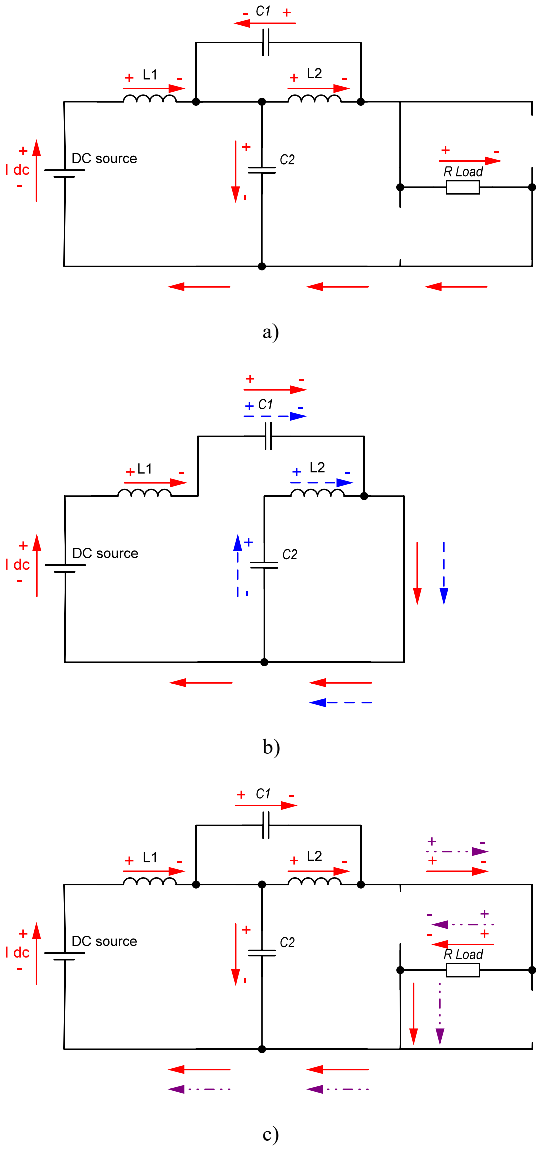
Generally, approaches on this task could be divided into two groups: topology improvements, or combined methods that implies both topology and control systems improvements. The most of topology approaches implementing the idea of z-source and cascaded multilevel topologies combination as the solution that allowed both output voltage increase and THD ratio reduction.

Combined methods imply both topology and control systems modernization methods to obtain THD ratio reduction. Also, some of the combined approaches include methods of the advanced inverter design that are based on output voltage spectra analysis.

This study is devoted to the practical analysis of the different topology improvements approaches on the problem of the z-source inverter THD ratio reduction, comparison of the obtained results, and discussion on the achieved results and the ways of further development of the existing technologies.

II. METHODS

To obtain the THD ratio of the z-source inverters that demonstrate different approaches on the problem, operation of the basic single level z-source inverter, three-level cascaded z-source inverter and three-level cascaded z-source inverter in which output cell's voltages are defined by the desirable output voltage decomposition results achieved by the orthogonal transformation were simulated in Simulink environment. All of the models are demonstrated in Fig.4 under abbreviations a), b) and c), correspondingly.



a)

b)

c)

Fig. 3 Operation cycle of quasi-z-source inverter. a) standard operation mode; b) "shoot-trough" operation mode; c) transmission of the stored energy to the load. Solid line – source current flow; dashed line – capacitors current flow; dotted line – inductors current flow

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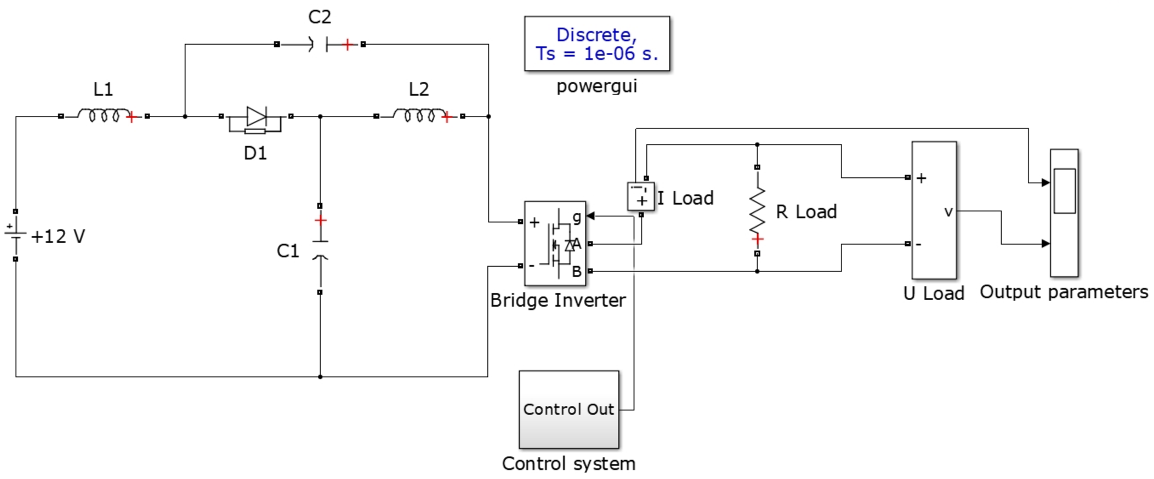
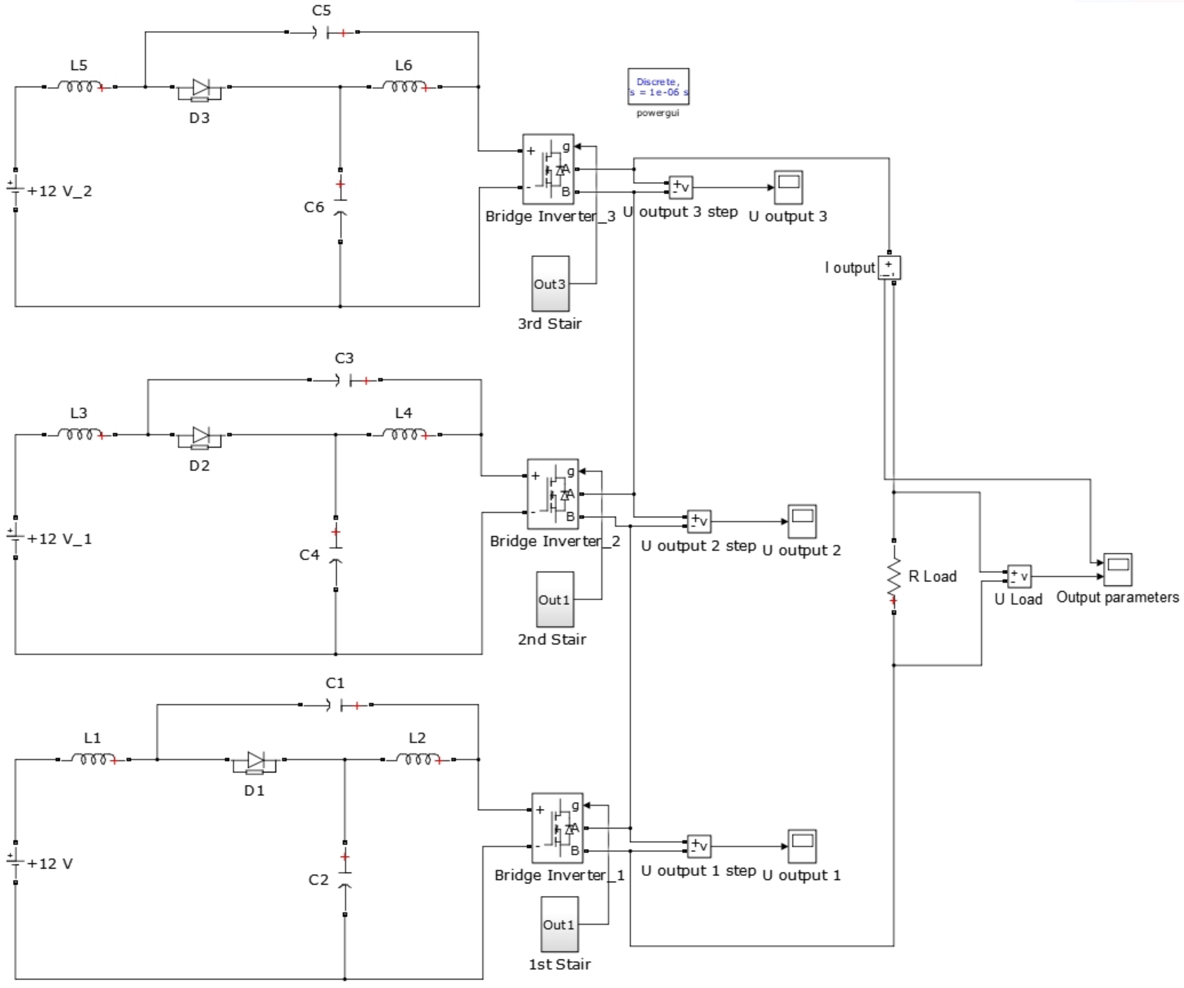


a)



b)

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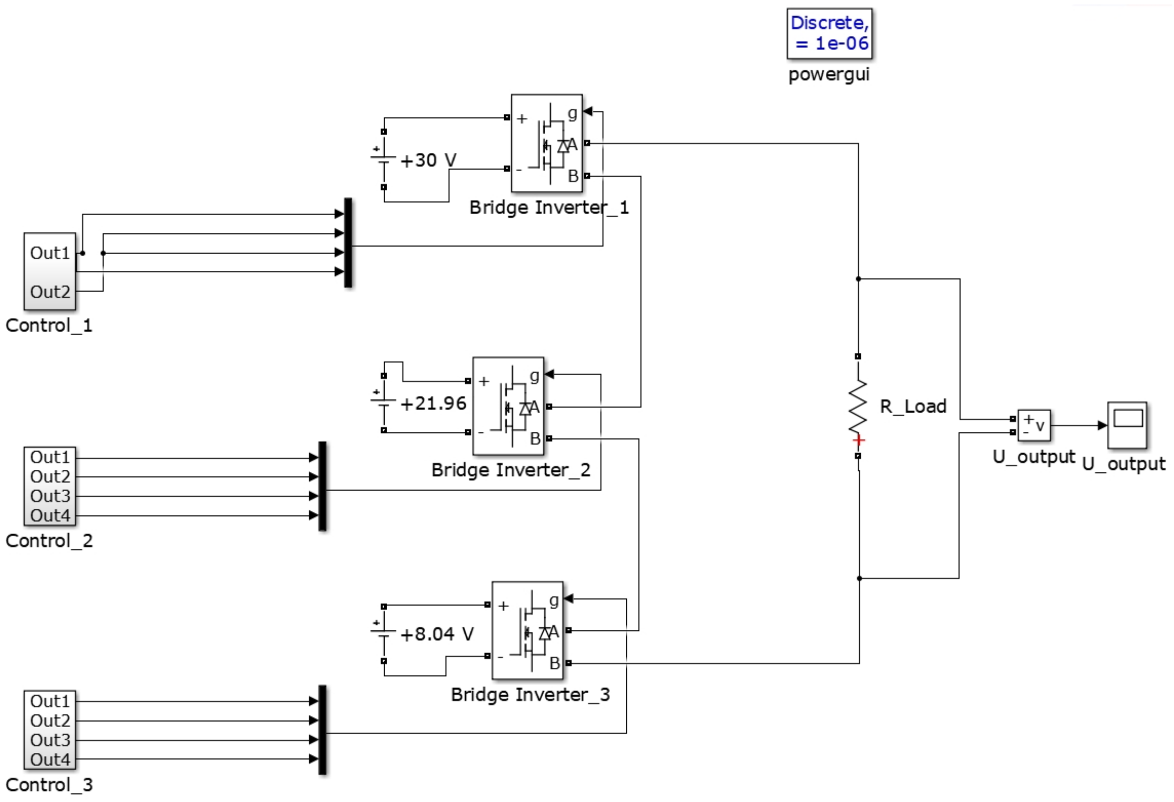

c)

Fig.4 Considered models of quasi-z-source inverters. a) quasi-z-source inverter; b) three-level cascaded quasi-z-source inverter; c) three-level cascaded inverter in which output cell's voltages is defined by the desirable output voltage decomposition results achieved by orthogonal transformation

Quasi-z-source voltage inverter model was designed to transform an input DC source voltage with an amplitude of 12 volts into AC voltage with an amplitude of 20 volts and frequency of 50 Hz for proper demonstration of the z-source's features. Inverter's schematic consists of the conventional full-bridge inverter, DC voltage source, 10 Ohms of resistive load, and impedance circuit that consists of two capacitors and inductors. Parameters of the impedance circuit were calculated according to the equations that were defined in the study "Z-source inverter"[9].

Three-level cascaded quasi-z-source inverter's model consists of three regular quasi-z-source inverters that are connected to the common resistive load in serial. Each of the inverters, that in cascaded multilevel inverters are named cells, is fed by a separate DC voltage source.

In this model, each cell is fed by a 12 volts DC source and generates 20 volts of AC voltage on the output. All of the cells output voltages sum up in the common load to form pseudo-sinusoidal load voltage with an amplitude of 60 volts and frequency equal 50 Hz.

The three-level cascaded inverter in which output cell's voltages are defined by the desirable output voltage spectra achieved by orthogonal transformation has the same circuitry as the standard three-level cascaded inverter. The only difference is that the amplitude of each cell is calculated according to the desired output voltage waveform decomposition achieved by direct orthogonal transformation.

The main idea of the method is that every sinusoidal waveform could be described as an orthogonal transformation row. Thus, the process of the cascaded multilevel inverter output voltage synthesis could be represented as follows: each cell of the inverter implements one of the reverse orthogonal transformation functions. The value coefficients of functions correspond to the amplitude of the discretized desirable waveform [15], [16]. Therefore an algorithm of its calculation consists of five following steps:

1) Approximation of the desired output voltage waveform by a normalized step function;
2) Decomposition of the obtained function into the orthogonal row on determined time period;
3) Synthesis of the output obtained pseudo-sinusoidal waveform through the implementation of the reverse orthogonal transition and determination of its THD ratio;
4) Elimination of the negligible coefficients and redetermination of the THD ratio;
5) Development of the cascaded multilevel inverter design based on the achieved quasi-sinusoidal waveform.

III. RESULTS

Obtained output voltage waveforms with corresponding graphs of the output voltage spectra are shown in Fig. 5, 6, and 7 respectively for quasi-z-source, three-

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level cascaded multilevel quasi-z-source and three-level cascaded inverter in which output cell's voltages are defined by the desirable output voltage decomposition achieved by orthogonal transformation. THD ratio values of all obtained output voltages are collected and demonstrated in Table 1.

As demonstrated by the THD ratio results shown in table 1 none of the considered topologies is capable to achieve 5 or less percent of an output signals THD ratio which is required by the international standards applied to the voltage quality of consumer power networks. Therefore not a single one of them could be directly connected to the consumer network without additional filtering that is commonly provided by passive LC-filters. However, the obtained reduction of the THD ratio led to the possibility of weight and size reduction of an output filter that could substantially reduce the overall size of the converter. Also, lower values of THD ratio could be reached by scaling the multilevel topologies through the addition of extra modules hence extra levels of the output voltage that will bring the output voltage waveform closer to the ideal sinusoidal shape.

TABLE 1 THD RATIO VALUES OF CONSIDERED INVERTER TOPOLOGIES FOR PHOTOVOLTAIC POWER SYSTEMS

Name of topology	THD ratio
Z-source inverter	29.19%
Three-level cascaded z-source inverter	19.69%
Three-level cascaded inverter in which output cell's voltages is defined by the desirable output voltage decomposition achieved by orthogonal transformation	15.26%

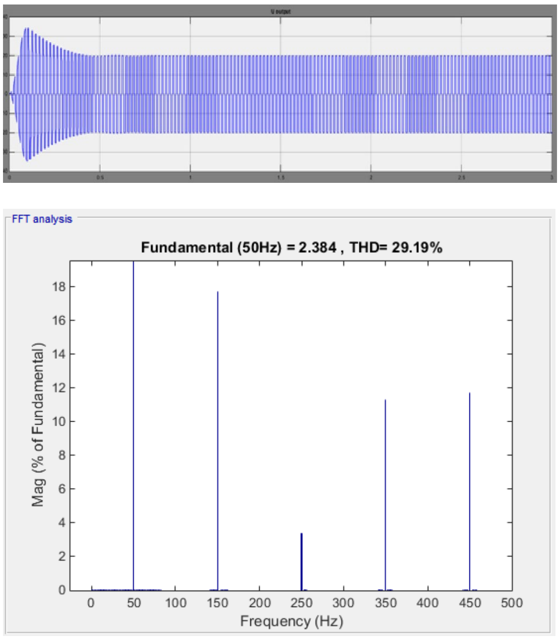

Fig. 5 Output voltage waveform and spectra of quasi-z-source inverter model

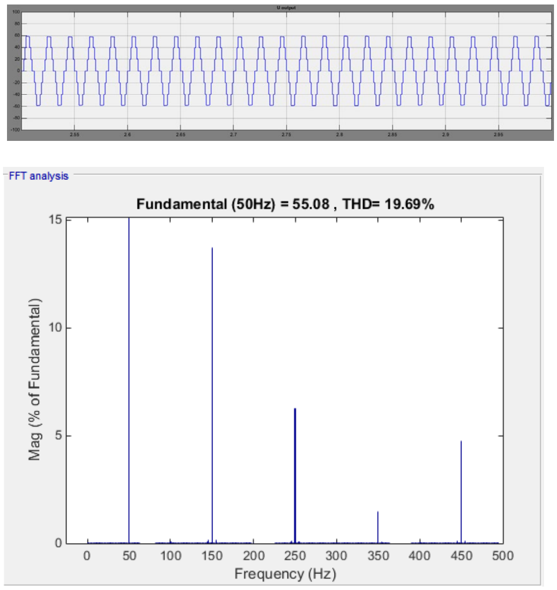

Fig. 6 Output voltage waveform and spectra of cascaded three-level quasi-z-source inverter model

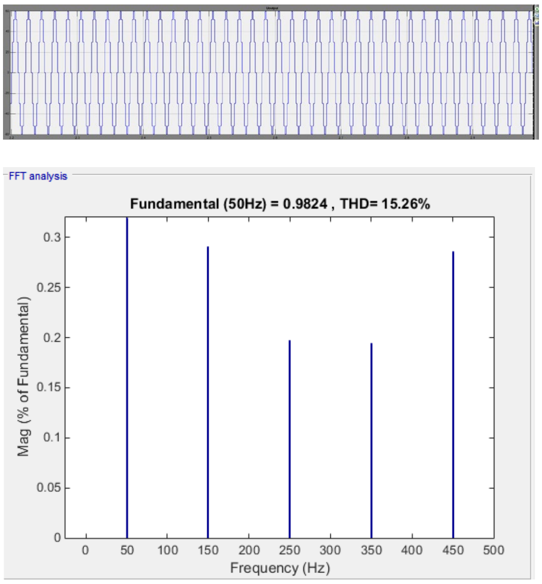

Fig. 7 Output voltage waveform and spectra of the multilevel inverter in which output cell's voltage is defined by the desirable output voltage decomposition results achieved by orthogonal transformation

IV. DISCUSSION

Summing up obtained practical results and theoretical considerations it could be outlined that thru the last decades of popularization and further development of solar power systems as a branch of renewable power systems, power inverters as its indispensable part made their own evolution way from conventional full- and half-bridge inverters to advanced topologies that could provide operation of the solar panels at their maximum power point and reduce THD ratio of the output voltage waveform without the addition of supplementary units. In present-day inverter solutions, the task of the power take-off maximization is usually resolved thru the implementation of z-source topologies. However, voltage increase feature of

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these topologies led to their main disadvantage – large values of the output voltage THD ratio. This problem could be solved either thru the application of the larger output passive filters that will increase the overall size and weight of the transforming device or implementation of the schematic improvements, one of the most effective of which is a combination of the quasi-z-source topology with the cascaded multilevel topology. As the main advantage of this solution could be named its ability to scale by addition of the new modules which could allow achieving the THD ratio of the output voltages on the level that meets international regulation standards without application of additional filtering solutions. All of the modules that form the resulting device could be unified and be built from the same components which could reduce production costs of the device. One of the main drawbacks that limit the use of the multilevel topologies on the modern inverter solutions is rather sophisticated control system that is getting more complex with the addition of every next module. With the application of z- or quasi-z-source topology as a base topology of the cell unit, development of the proper control system could become even more complicated task due to the demand of a "shoot-through" state of power switches addition in every cell of the general device. With the implementation of microcontrollers, this task can be sufficiently simplified in terms of a hardware issue but the software development of such products still remains fairly complex [17],[18],[19]. Inclusion of the desired voltage waveform forming methods to a multilevel inverter, in their turn, would add extra demands to the output voltage stability of every inverter's cell. Even the slightest instability of their output voltages could lead to significant changes in output voltage's spectra and, therefore, in THD ratio, making the implementation of such solution quite useless. However, further development of cascaded multilevel cell's output voltage stabilization methods and control techniques in the field of photovoltaic converters technologies may present the way of overcoming these limitations, which makes the investigation of such methods and determination of their implementation ways towards cascaded-z-source multilevel topologies a perspective direction in the field of the inverters THD ratio reduction task resolution.

According to the provided discussion, it may seem that the optimal solution for modern inverter devices in solar power systems in terms of THD ratio reduction is a combination of the multilevel topology with size-reduced output passive filter. This solution is simultaneously able to reduce the size of the output filter, avoid excessive sophistication of the control system, and achieve the desired THD level. Researches in a field of new control algorithms, that will simplify the software development process for the control systems, and stabilization of the cell's output voltages methods could be defined as a rather perspective way of the further solar power systems inverters' technology evolution that will allow to completely exclude passive filters from the inverter systems.

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Надійшла до редакції 08 липня 2020 р.

DOI: 10.20535/2523-4455.mea.207543

УДК 621.314.58

Зниження рівня нелінійних спотворень вихідної напруги інверторів в системах електроживлення з сонячними панелями

Федін[f] І. С., ORCID 0000-0003-0264-5067
Терещенко[s] Т. О., д.т.н. проф., ORCID 0000-0003-4009-2854
Ямненко[s] Ю. С., д.т.н. проф., ORCID 0000-0002-9796-6420
Кафедра електронних пристроїв та систем
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського», ROR 00syn5v21
Київ, Україна

***Анотація*—Використання сонячних панелей широко розповсюджене при побудові сучасних користувацьких систем електроживлення. Поряд з безпосереднім розвитком сонячних джерел електроживлення власного еволюційного шляху зазнали конвертори, що входять до складу систем електроживлення з сонячними панелями. У основі їх розвитку постала необхідність у одночасному забезпеченні виконання вимог з максимізації відбору потужності сонячних панелей та забезпечення рівня коефіцієнту нелінійних спотворень (КНС) вихідної напруги перетворювача на рівні, визначеному міжнародним законодавством щодо якості напруги користувацької мережі. У сучасних системах електроживлення з використанням сонячних панелей широкого застосування зазнали інвертори з z- та квазі-z-топологіями через можливість забезпечення роботи системи у точці відбору максимальної потужності сонячної батареї без використання додаткових перетворювачів. Значення КНС даних перетворювачів перевищує параметри визначені міжнародними стандартами, що визначає актуальність задачі пошуків методів його зниження. Дана стаття присвячена визначенню, порівнянню та обговоренню методів зниження КНС для топологій інверторів систем електроживлення з сонячними панелями. У практичній частині статті описані моделі інверторів, створених за квазі-z, каскадною багаторівневою квазі-z-топологією та каскадною багаторівневою топологією з визначенням рівнів вихідних напруг комірок інвертора на базі визначення спектру бажаної вихідної напруги шляхом застосування ортогонального ОБ-перетворення з метою демонстрації, практичної перевірки та порівняння різних підходів до вирішення задачі зменшення КНС систем електроживлення з сонячними панелями. В результаті проведених симуляцій були отримані спектри та значення КНС вихідної напруги кожної з моделей. Виходячи з них, метод на базі визначення рівнів вихідних напруг комірок інвертора на базі визначення спектру бажаної вихідної напруги шляхом ортогонального ОБ-перетворення дозволив отримати найнижче, серед досліджених зразків, значення КНС вихідної напруги. На основі переваг та недоліків кожного з методів зниження КНС, визначених у розділі обговорення, застосування каскадної багаторівневої топології у поєднанні зі зменшеним за габаритними розмірами пасивним фільтром визначено методом, що робить можливим одночасне досягнення необхідного значення коефіцієнту нелінійних спотворень, зменшення розмірів вихідного фільтру та відсутність додаткового ускладнення будови систем керування. Перспективним напрямком подальшого розвитку тематики зниження КНС вихідної напруги систем електроживлення з сонячними панелями визначено дослідження в сфері модернізації систем керування, стабілізації вихідної напруги комірок багаторівневих інверторів та пошуку і практичної перевірки шляхів застосування методу визначення рівнів вихідних напруг комірок інвертора на базі визначення спектру бажаної вихідної напруги шляхом ортогонального ОБ-перетворення до топології каскадного багаторівневого квазі-z-інвертора. Дана можливість може привести до його популяризації при розробці нових перетворювачів, що, в свою чергу, може призвести до повної відмови від застосування пасивних фільтрів в результаті відсутності необхідності у додатковій фільтрації вихідної напруги.**

Ключові слова* — *інвертори з імпедансним ланцюгом у вхідному колі; системи електроживлення з відновлювальними джерелами; каскадні багаторівневі інвертори; коефіцієнт нелінійних спотворень; якість вихідної напруги.