–Торайғыров университетінің хабаршысы
ҒЫЛЫМИ ЖУРНАЛЫ

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Торайғыров университетінің ХАБАРШЫСЫ

Энергетикалық сериясы

1997 жылдан бастап шығады

ВЕСТНИК Торайгыров университета

Энергетическая серия

Издается с 1997 года

ISSN 2710-3420

№ 1 (2024)

ПАВЛОДАР

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Энергетическая серия
выходит 4 раза в год

СВИДЕТЕЛЬСТВО
о постановке на переучет периодического печатного издания,
информационного агентства и сетевого издания
№ 14310-Ж
выдано
Министерство информации и общественного развития
Республики Казахстан

Тематическая направленность
публикация материалов в области электроэнергетики,
электротехнологии, автоматизации, автоматизированных и информационных
систем, электромеханики и теплоэнергетики

Подписной индекс – 76136

https://doi.org/10.48081/KQTB8442

SRSTI44.01.05

https://doi.org/10.48081/MFVJ6733

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ANALYSIS OF CIRCUITS WITH UNIFORM PHASE SHIFT OF INVERTER CELLS

The article discusses the methods of constructing an inverter with summation of the power conversion cell currents. A computer simulation of the proposed load current distribution schemes of a multicellular inverter with a phase shift of cells has been carried out. When considering the task of increasing the maximum power of the inverter, taking into account the existing element base, it becomes quite obvious that the design of high-power inverters to obtain high performance without load distribution on the flows is very difficult. One of the most important tasks of the organization of parallel operation of inverters is to ensure a uniform distribution of currents between the cells of inverters, they must be synchronized in all parameters (phase, frequency and amplitude). Synchronization must be operational in any modes (nominal, transient and emergency). The uniform distribution of the load current across the inverter cells depends on the phase shift of the output voltages caused by the non-synchronicity of the voltage frequencies generated at the outputs of the inverter cells. An imbalance of one degree between the phases of the output voltages of the two cells leads to a redistribution of power, which can reach over fifty percentages. If the output voltage of one cell shifts forward in phase, then it takes over most of the power of the total load, which in the case of the same output voltage amplitudes will indicate an increase in the current consumption of the leading cell. To ensure the energy balance of the two cells, it is necessary to add *just the frequency of the output voltage of the cell with the leading phase. This balancing should occur with high speed.*

Keywords: power conversion, inverter, phase shift, high speed, distribution, parallel connection, transistors, synchronization.

Introduction

At which phase shift the power is most efficiently transferred to the load. Since the power conversion cell works in the key mode for high efficiency, and an LC filter is used to obtain a sinusoidal voltage, then in the limit at the point of summation of the CPS with a choke at the output, we represent a sinusoidal source.

In [1], various structures of parallel switching circuits of inverters with the following features are given:

- The phase of the inverter is formed from a series of parallel-connected power conversion cell (PCC) controlled by a single controller. All power transistors are passively locked by their own gate resistor. The connection of the AC and DC circuits is symmetrical.

- Parallel connection of inverters with integrated control circuit boards. The spread of the parameters of the power circuits leads to the need to combine the outputs of inverters through equalizing chokes.

- Parallel connection of inverter units with a common DC bus, where inverters have a dedicated control board that operate from a single PWM controller. Due to the spread of the time characteristics of the control circuits for combining PBX outputs, it is very likely that equalizing inductors are introduced into the power part.

- Parallel connection of inverters and a single PWM and an additional measurement of the distribution of output currents of inverters, however, this ideology differs in a rather complex control scheme.

- Subordinate regulation, which ensures high reliability, in which the control board has a common input and several isolated output channels. Each channel has its own inverter. In this case, equalizing chokes can be excluded – the failure of one of the inverters does not affect the operation as a whole.

- Complete galvanic isolation at the input or output of parallel inverters with independent control boards. The modular principle of construction of inverter units has been widely used for many years in uninterruptible power supply systems.

This allows, if necessary, to increase the power of the system by increasing the number of consumers and the necessary redundancy of the system on the principle of «*n+x*». Uniform distribution of currents between modules refers to one and difficult tasks and, in general, is ensured by matching the output characteristics of the modules: voltage rating and internal resistance.

Materials and methods

A large number of works have been devoted to parallel switching on the output of single-phase inverters and many foreign manufacturers have established serial production of three-phase inverters with module power up to several tens of kilowatts, using an independent system synchronization principle from any of the inverters included in it [2]. At the moment, the task of load separation of inverter units is most fully solved in industrial uninterruptible power supply (UPS). Figure 1 shows the application of parallel switching of inverters in the structure of an uninterruptible power supply.

The number of modules connected to the load in parallel can be reached with information communication between the modules, both via a digital bus, and with a combination of analog and digital signals in the bus. When a backup module is connected, the module is identified, and if the system is in good condition, this module is connected by the system to the load and takes on a proportional part of the load current [3].

If one module fails, the system disables its load buses. As a result, the faulty inverter is switched off without disrupting the performance of the entire system.

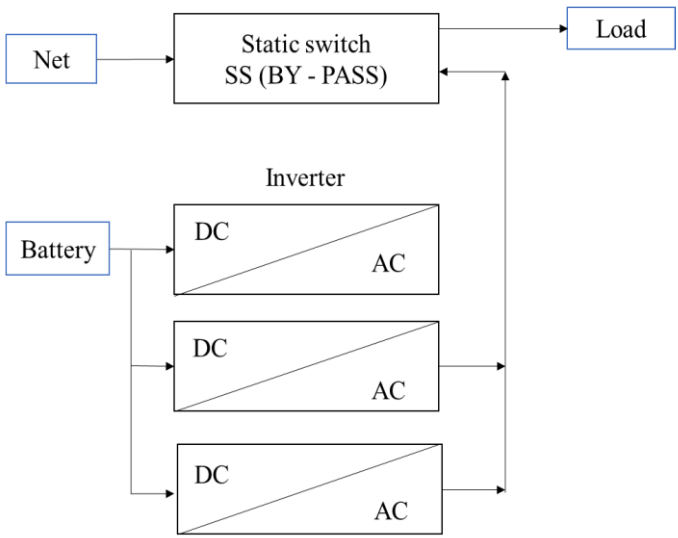

Figure 1 – Parallel inclusion of inverter blocks in the UPS

The most widely developed control of modules is based on the subordinate principle of «master-slave». With this control method, there is no redundancy of the master inverter that synchronizes the operation of the «slave» inverters. In addition, the use of a common switching unit and uniform distribution of load current is required. All this reduces the fault tolerance of the system as a whole.

A distinctive feature of a multimodule system is redundancy, which provides increased reliability of the system due to: backup power modules and backup battery modules [4]. During the operation of the system, a «hot swap of modules» is possible (modules can be replaced promptly during the operation of the system). A malfunction of one of the modules leads to its automatic shutdown, while the operability of the entire system is not disrupted. When installing a new module, a self-diagnosis of its condition is carried out and its inclusion in operation. However, with a zero phase shift of inverters, certain technical difficulties in organizing parallel operation of inverters are noted in the literature.

As shown earlier, the main problem with parallel switching of cells is the uneven distribution of currents between cells caused by the spread of internal parameters of inverters, so, for example, different frequencies of the output voltages of the inverter lead to distortion of the voltage form in the form of beats. The literature describes solutions that provide parallel operation of inverters in terms of synchronization of the initial phases of the inverter, current amplitudes and voltage frequency [5]. It should be noted that the described methods consider the formation of voltage at the output of an inverter with a low content of higher harmonics [6].

In the presence of a phase shift, we also proceed from the position that for high efficiency the SPA operates in the key mode, and an LC filter is used to obtain a sinusoidal voltage. PWM methods are used to regulate the output voltage. In this case, the reference signal is taken as a single one, and the sawtooth signal of each cell with the corresponding phase shift, so each cell operates with its own phase of PWM signals [7].

Figure 2 shows an equivalent scheme for this case. Due to the phase shift of the control voltage, PWM regulation of each cell is obtained.

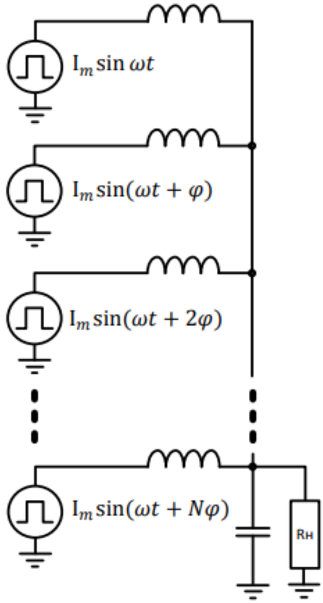

Figure 2 – Diagram of a multicellular inverter by summing the cell current and a non-zero phase shift

The principle of formation is as follows: the sequence of output pulses of each CNN is formed on the basis of a single reference sinusoidal signal and a sawtooth voltage with its own phase shift of each cell, Figure 3.

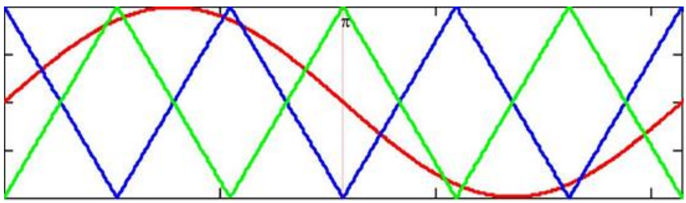

Figure 3 – Modulator input signals with a single reference signal and sawtooth voltage with uniform shift

Figure 4 shows the voltages for two consecutive NPS, and Figure 5 shows the total output voltage of the power cascades of the cells. By increasing the number of sawtooth signals and the number of cells, it is possible to achieve a significant reduction in the switching frequency of transistors with a relatively high frequency of the formation of output voltage fronts [8]. However, with such control, currents occur that bypass the load, which significantly reduces the efficiency of power transmission to the load. To show this, let's consider the current circuits arising from such control.

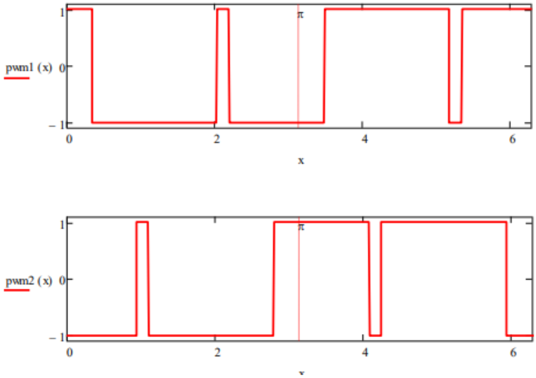

Figure 4 – Formation of switching moments of transistors of each cell

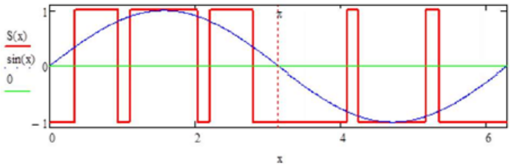

Figure 5 – Voltage form at the input of the power filter

In [9] various circuit design options for constructing a power transformer cell are given. Analysis of the literature allows us to conclude that the most functionally suitable structure with a minimum of switching elements is a half-bridge power converter cell.

Results and discussion

The schematic diagram of a multicellular inverter with parallel connection of half-bridge PCC to a DC voltage source is shown in Figure 6. Consider the possibility of using a phase shift of the inverter cells to form an approximated sinusoidal output voltage. The difference from the traditional scheme of parallel switching of inverters is the synchronized shift of the initial phase of the inverter cells [10].

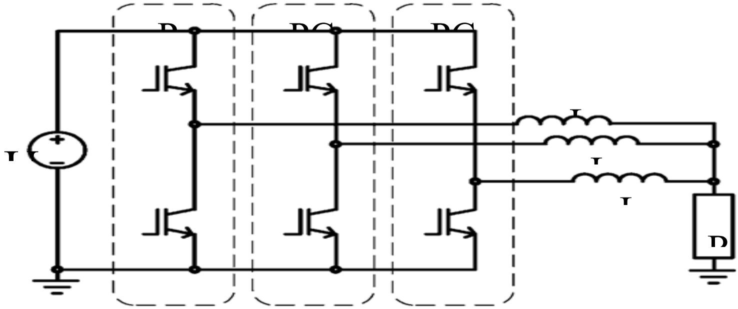

Figure 6 – Diagram of a simulated inverter with a three-level output voltage

In accordance with the schematic diagram, a computer model has been developed to study the processes occurring in the inverter. As an example, an inverter consisting of three cells forming a three-level voltage with a uniform phase shift is taken.

The simulation results are shown in Figure 7-8. The results obtained show the shape of the low-quality output voltage and the corresponding spectral composition. However, when considering the current distribution graphs, the problem of the occurrence of current flow circuits bypassing the load becomes obvious.

Consider the switching of keys with the intersection of the inclusion of the upper and lower keys of the inverter cells for the occurrence of currents flowing bypassing the load.

From the above current flow diagrams, it can be seen that current flow circuits bypassing the load can occur in the circuit when any combination of the upper and lower keys of the inverter is turned on simultaneously.

One of the possible options for eliminating bypass circuit currents is the introduction of an additional transistor rack and differentiation of the operation of the lower and upper keys of the inverter cells.

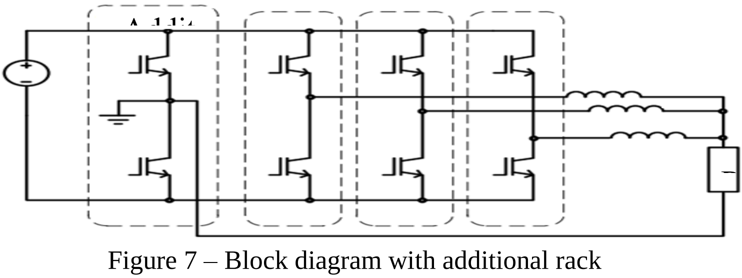

Figure 7 – Block diagram with additional rack

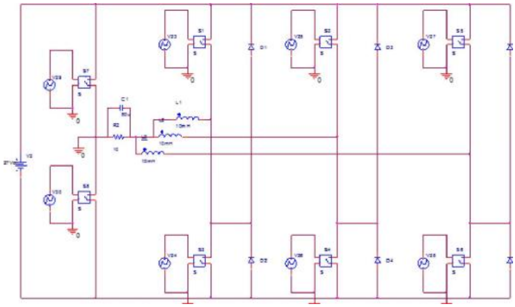

Figure 8 – Diagram of a model of a three-level voltage inverter with switching of the upper and lower keys separately

The simulation results are presented in Figures 9, 10.

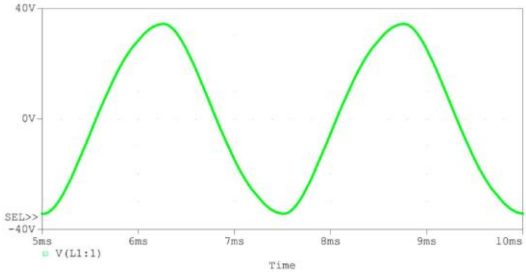

Figure 9 – The form of the output voltage of the inverter with an additional rack

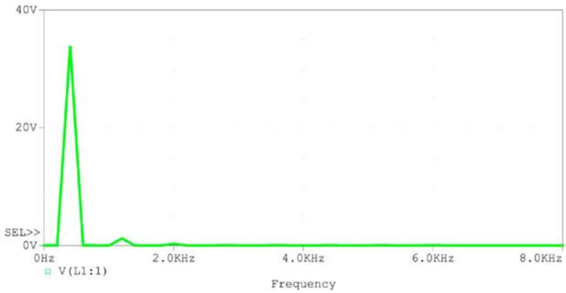

Figure 10 – Spectral composition of the output voltage of an inverter with an additional rack

The disadvantage of this scheme is an incomplete load distribution between the cells of the inverter.

In the case of a uniform phase shift of the inverter cells, the load current on a single inverter cell can reach the full load current. Such a scheme becomes irrelevant, despite the possibility of forming an output step voltage.

Conclusion

In this article, the methods of constructing a multicellular inverter with summation of the PCC currents are considered and the following results are obtained:

1 The analysis of existing solutions has shown that for a multicellular inverter, the most appropriate scheme of construction is a half-bridge scheme of the PCC.

2 An analytical expression has been obtained showing that, with parallel operation of the NPS, the maximum power is transferred to the load at zero phase shift.

3 A study of existing solutions has been conducted, it has been shown that ensuring the operation of a zero phase shift joint venture requires significant costs for the organization of management and complication of circuit solutions, compared with the operation of a phase shift joint venture.

4 A computer simulation of a multicellular inverter with summation of CPS currents and linear phase shift with different types of key switching was carried out, results for comparative analysis were obtained.

5 It is shown that when summing up the currents of the CNR and the two-stroke switching of the CNR, the occurrence of current flow circuits is possible, bypassing the load, with single-stroke switching of the CNR, full loading of cells is impossible, which significantly reduces the efficiency of such inverters.

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Received 09.02.24.

Received in revised form 15.02.24.

Accepted for publication 04.03.24.

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Поступило в редакцию 09.02.24.

Поступило с исправлениями 15.02.24.

Принято в печать 04.03.24.

АНАЛИЗ СХЕМ С ОДНОРОДНЫМ СДВИГОМ ФАЗ ИНВЕРТОРНЫХ ЯЧЕЙЕЕК

В статье рассмотрены методы построения инвертора с суммированием токов ячеек преобразователя мощности.

Проведено компьютерное моделирование предложенных схем распределения тока нагрузки многоячеечного инвертора со сдвигом фаз ячеек. При рассмотрении задачи повышения максимальной мощности инвертора с учетом существующей элементной базы становится совершенно очевидным, что проектирование мощных инверторов для получения высоких характеристик без распределения нагрузки по потокам весьма затруднительно. Одной из важнейших задач организации параллельной работы инверторов является обеспечение равномерного распределения токов между ячейками инверторов, они должны быть синхронизированы по всем параметрам (фазе, частоте и амплитуде). Синхронизация должна работать в любых режимах (номинальном, переходном и аварийном). Равномерное распределение тока нагрузки по ячейкам инвертора зависит от сдвига фаз выходных напряжений, вызванного несинхронностью частот напряжений, формируемых на выходах ячеек инвертора. Дисбаланс в один градус между фазами выходных напряжений двух ячеек приводит к перераспределению мощности, которое может достигать более пятидесяти процентов. Если выходное напряжение одной ячейки смещается вперед по фазе, то оно берет на себя большую часть мощности общей нагрузки, что в случае одинаковых амплитуд выходного напряжения будет свидетельствовать об увеличении тока потребления ведущей ячейки. Для обеспечения энергетического баланса двух ячеек необходимо регулировать частоту выходного напряжения ячейки с опережающей фазой. Эта балансировка должна происходить с высокой скоростью.

Ключевые слова: преобразование мощности, инвертор, фазовый сдвиг, высокая скорость, распределение, параллельное соединение, транзисторы, синхронизация.

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Қазақстан Республикасы, Қарағанды

Поступило в редакцию 09.02.24.

Поступило с исправлениями 15.02.24.

Принято в печать 04.03.24.

ИНВЕРТОР ҰЯШЫҚТАРЫНЫҢ БІРТЕКТІ ФАЗАЛЫҚ ЫҒЫСУ СХЕМАЛАРЫН ТАЛДАУ

Мақалада түрлендіргіштегі ұяшық токтарын қосатын инверторды құру әдістері қарастырылған. Ұяшықтардың фазалық ығысуы бар көп ұяшықты инвертордың жүктеме тогын бөлудің ұсынылған схемаларын компьютерлік модельдеу жүргізілді. Қолданыстағы элементтер базасын ескере отырып, инвертордың максималды қуатын арттыру мәселесін қарастырған кезде, жүктемені ағындарға таратпай жоғары өнімділікті алу үшін күштік инверторларды жобалау өте қиын екендігі айқын болады. Инверторлардың параллель жұмысын ұйымдастырудың маңызды мәселелерінің бірі – инвертор ұяшықтары арасында токтардың біркелкі таралуын қамтамасыз ету, олар барлық параметрлер бойынша (фаза, жиілік және амплитуда) синхрондалуы керек. Синхрондау кез келген режимде жұмыс істеуі керек (номиналды, өтпелі және апаттық). Инвертор ұяшықтары бойынша жүктеме тогының біртекті таралуы инвертор ұяшықтарының шыға берісінде пайда болатын кернеу жиіліктерінің синхрондалмауынан туындаған шығыс кернеулерінің фазалық ығысуына байланысты. Екі ұяшықтың шығыс кернеуінің фазалары арасындағы бір градус болатын дәрежедегі теңгерімсіздік қуаттың қайта бөлінуіне әкеледі, ол елу пайыздан асады. Егер бір ұяшықтың шығыс кернеуі фаза бойынша алға жылжитын болса, онда ол жалпы жүктеме қуатының көп бөлігін алады, бұл шығыс кернеуінің амплитудасы бірдей болған жағдайда жетекші ұяшықтың тұтыну тогының жоғарылауын көрсетеді. Екі ұяшықтың энергетикалық балансын қамтамасыз ету үшін озық фазасы бар ұяшықтың шығыс кернеуінің жиілігін реттеу қажет. Бұл теңгерім жоғары жылдамдықпен жүруі керек.

Кілтті сөздер: түрлендіру, инвертор, фазалық сдысу, жоғары жылдамдық, таралу, параллель байланыс, транзисторлар, синхрондау.

Теруге 06.03.2024 ж. жіберілді. Басуға 29.03.2024 ж. қол қойылды.
Электронды баспа
29.9 Mb RAM
Шартты баспа табағы 22,2. Таралымы 300 дана. Бағасы келісім бойынша.
Компьютерде беттеген: А. К. Мыржикова
Корректор: А. Р. Омарова
Тапсырыс №4204

Сдано в набор 06.03.2024 г. Подписано в печать 29.03.2024 г.
Электронное издание
29.9 Mb RAM
Усл. печ. л. 22,2. Тираж 300 экз. Цена договорная.
Компьютерная верстка: А. К. Мыржикова
Корректор: А. Р. Омарова
Заказ № 4204

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