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A BIDIRECTIONAL DC–AC CONVERTER BASED ON AN ASYMMETRIC INVERTER FOR HYBRID ENERGY STORAGE SYSTEMS

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This paper presents the analysis of electromagnetic processes in a bidirectional DC-AC converter based on an asymmetric inverter with magnetically coupled inductors, as well as the determination of its parameters aimed at improving energy efficiency. The study is based on the state-space averaging method and simulation modelling techniques. As a result, analytical expressions for calculating currents in the asymmetric inverter with magnetically coupled inductors during switching intervals are derived. The relationship between the inductances of the inductors and the parameters of the input and output power sources is established, under which circulating currents in the inverter circuits are eliminated, resulting in reduced static power losses in the converter. In this research, new analytical and graphical relationships are obtained for the operation of a bidirectional DC-AC converter in active and reactive power transfer modes, thereby extending previous models of asymmetric DC-DC converters. The derived relationships enable improved converter efficiency at the design stage by minimizing power losses caused by circulating currents through optimal parameter selection. References 24, figures 8.

Keywords: energy storage systems, bidirectional DC–AC converter, asymmetric inverter topology, highly dynamic bidirectional power conversion, hybrid electric vehicle.

Battery energy storage systems are widely used to ensure energy storage, retention, and efficient utilization in AC power networks [1]. Their main application areas include energy storage systems, uninterruptible power supplies (UPS) [2], electric and hybrid electric vehicles [3–5], as well as renewable energy generation systems [6]. Energy exchange between the storage unit and the AC grid is performed using bidirectional semiconductor DC-AC converters. At present, bidirectional converters are widely employed to enable power flow in both directions.

Particular attention should be given to the application of bidirectional DC-AC converters in electric transportation systems. Hybrid and electric vehicles provide a clear illustration of the operating principles and practical use of such converters. Hybrid energy storage systems, such as fuel cell–battery configurations, are increasingly adopted in modern vehicles. In these systems, power distribution occurs at multiple voltage levels due to the presence of energy storage units. Both charging and discharging processes of the battery – particularly during generator operation driven by an internal combustion engine or during regenerative braking – require bidirectional energy conversion [7]. Vehicle dynamics involve rapid acceleration, which demands high power from the onboard energy system [8]. At the same time, during braking, regenerative systems generate excess energy that must be efficiently stored to improve overall energy efficiency and extend driving range. This energy can be stored either in batteries or in supercapacitors, which are used to support fast dynamic responses such as vehicle acceleration [9].

The architectures of energy systems in different vehicles may vary; however, the overall concept – based on the use of batteries, supercapacitors, and bidirectional converter – remains consistent. The application of bidirectional converter topologies enables the development of compact, energy-efficient, and adaptive solutions, which are critically important for highly dynamic energy systems such as electric vehicles, energy storage systems, and regenerative energy systems. Fig. 1 shows the structure of an energy conversion and storage system based on electric vehicles.

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The bidirectional DC-AC converter operates in two modes. The first mode is the rectification mode, in which the converter operates as an active rectifier, enabling power transfer from the three-phase AC grid to the DC bus. The second mode is the inversion mode, where power flows from the DC bus to the three-phase AC grid, and the converter operates as a voltage source inverter.

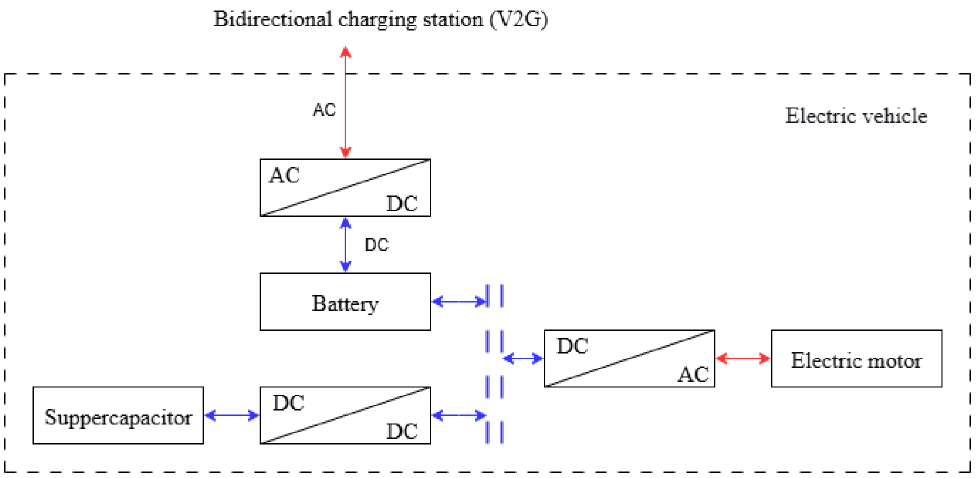


Fig. 1

The integration of battery energy storage systems into AC grids is becoming increasingly widespread due to the need for optimization of hybrid power sources. Considering the require-ments for reducing converter cost and size, bidirectional DC-AC converters represent an effective solution by enabling the use of shared power com-ponents for energy transfer in both directions. Currently, a wide range of circuit topologies for bidirectional semiconductor converters has been developed, with their selection depending on specific application requirements and operating conditions. Numerous studies have focused on the classification of bidirectional converters based on topology, the presence of galvanic isolation between input and output stages, and control strategies [10–13].

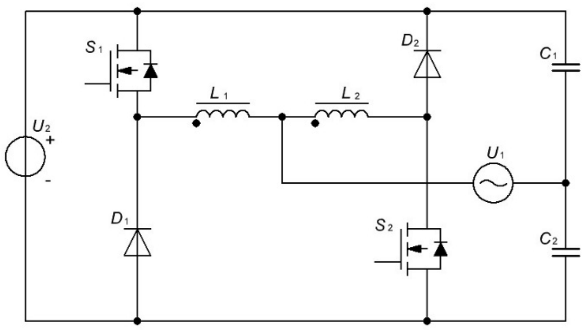


Fig. 2

Bidirectional DC-AC converters based on asymmetric inverter topology are widely used in energy storage systems [11, 14–17], as shown in Fig. 2. This topology offers several advantages compared to conventional bridge inverters. First, shoot-through currents are inherently eliminated, since active power switches are not connected in series within each phase leg, which prevents their occurrence even if all switches are turned on simultaneously. Second, switching losses associated with reverse recovery are significantly reduced, as there is no current path through the intrinsic body diodes of the power switches. Third, the inverter can operate without dead time under pulse-width modulation (PWM), eliminating issues related to shoot-through currents and enabling higher switching frequencies. Fourth, a high dynamic response is ensured during transitions between charging and discharging modes, which contributes to more efficient energy utilization, particularly during regenerative braking in electric transport [14], and represents a significant advantage of this converter for application in automotive hybrid energy storage systems.

Bidirectional DC-AC converters based on asymmetric inverter topology can be implemented using two types of inductors: magnetically coupled and non-coupled inductors. As shown by the analysis of inverter operation, the main difference between these implementations lies in the transition time between energy storage and energy delivery modes [14]. In converters with non-coupled inductors, the transition time is determined by the inductance value. In contrast, for magnetically coupled inductors, the transition time is governed by the leakage inductance between the windings. Therefore, due to reduced leakage inductance, converters with magnetically coupled inductors can achieve faster dynamic response, which is critical for many applications.

Despite these advantages, the use of magnetically coupled inductors in an asymmetric inverter comes with a number of drawbacks. As demonstrated in papers [11, 14, 15, 18–20], circulating currents may occur in the circuits of such an inverter Fig. 2, which results in additional load on the power switches and increased power losses. Furthermore, the occurrence of circulating currents is facilitated by certain ratios of the power supply parameters on the low-voltage and high-voltage sides [14, 21, 22]. Thus, in converters with non-magnetically coupled inductors, there are no circulating currents; however, this comes at the cost of degraded dynamic performance, specifically an increased duration of transient processes when direction of energy flow changes. In contrast, an asymmetric inverter with magnetically coupled inductors offers high speed performance, but under certain circumstances, the presence of circulating currents results in excessive power losses. Therefore, bi-directional DC-AC converters based on an asymmetric inverter require further research to reduce circulating currents while maintaining high speed performance. One of the key tools for addressing this challenge is the development of mathematical and simulation models that enable the study of the processes occurring within converters.

Compared with previous studies [14, 21, 22], which were mainly focused on bidirectional DC-DC converter topologies and specific operating modes, the present work extends the developed analytical framework to bidirectional DC–AC conversion systems operating in inversion, active rectification, and reactive power transfer modes. In addition, new graphical relationships are obtained for determining the operating boundaries of the asymmetric inverter in hybrid AC electrical energy storage systems.

The **objective** of this work is to develop mathematical and simulation models of an asymmetric inverter with magnetically coupled inductors for a bi-directional DC-AC converter and to provide recommendations for selecting inductor parameters to enhance the converter's efficiency.

The bidirectional DC-AC converter based on an asymmetric inverter with magnetically coupled inductors was analysed using the PSIM circuit simulation environment, based on the developed simulation model Fig. 3. The model includes magnetically coupled inductors L_1=L_2=L=2 mH and an additional inductor L_s. The following assumptions are adopted: switching of the power devices is considered instantaneous; their on-state resistance is assumed to be zero; the winding resistance of the inductors is also neglected. In the circuit shown in Fig. 3, the amplitude of the input voltage source is U_1=220 V; the voltages across the capacitors are $U_{C_1} = U_{C_2} = U_2/2$, where U_2=500 V. For improved clarity of the simulation results, the grid frequency is set to 500 Hz, and the pulse-width modulation (PWM) frequency is 20 kHz.

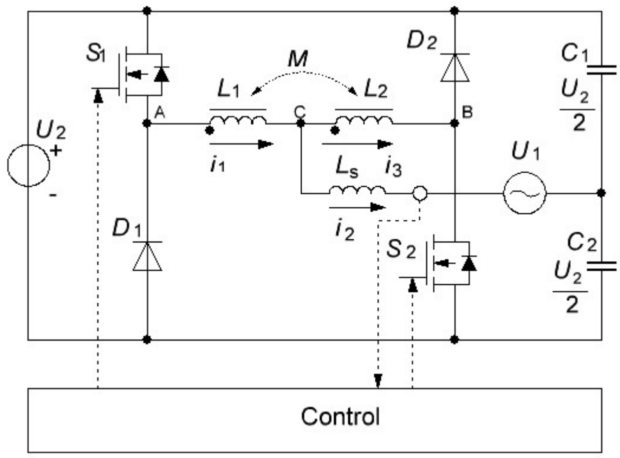


Fig. 3

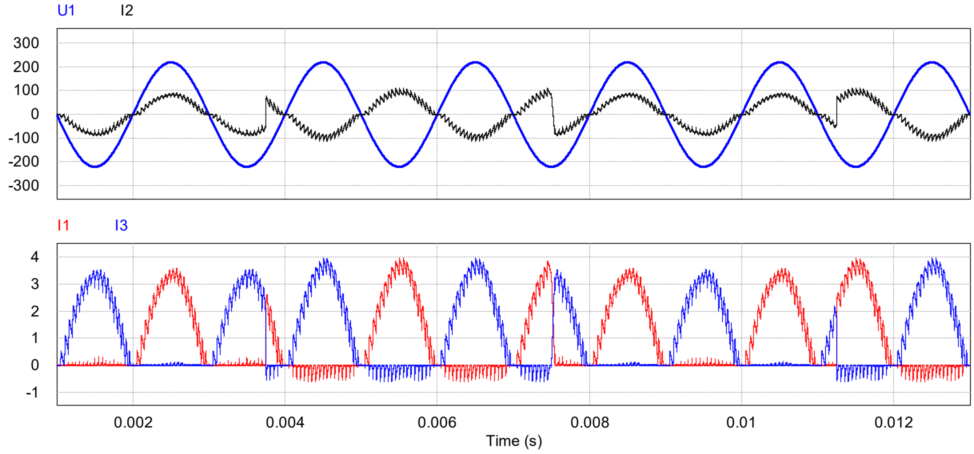
Inductors L_1 and L_2 provide current limitation during switching intervals, particularly in conditions where upper and lower power switches may be simultaneously turned on and also perform the function of an inductive filter. An additional inductor L_s, connected between the common node "*c*" of inductors L_1 and L_2 and the source U_1, further limits the load current i_2. The mutual inductance between inductors L_1 and L_2 is denoted as M.

Several operating modes can be identified for the bidirectional DC-AC converter Fig. 3. In the first mode, the converter transfers active power from the DC source (energy storage system) to the AC grid, with the grid voltage and inverter output current being in phase. In the second mode, the converter operates as an active rectifier, generating a charging current for the energy storage system with low harmonic distortion. In this case, the grid voltage and the inverter input current are in anti-phase 180° phase shift. In more advanced applications, DC-AC converters can also be used for reactive power compensation.

In the rectification mode with active power consumption, switch S_1 and diode $_{D1}$ conduct during the positive half-cycle, while switch S_2 and diode D_2 conduct during the negative half-cycle Fig. 3. In inverter mode with active power transfer, the processes are analogous to the rectification mode, except for the phase relationship between voltage and current, resulting in power transfer from the DC source to the AC grid.

Fig. 4, *a* presents the simulation results of the inverter and rectifier operating modes of the asymmetric inverter in the absence of the additional inductance L_s=0. As observed from the results, currents i_1 and i_3 coexist simultaneously in both inverter and rectifier modes. The current flowing simultaneously through the two magnetically coupled inductors L_1 and L_2 represents the circulating current [18, 21, 22]. The analysis shows that the circulating current may flow through diodes D_1 or D_2, as well as through the antiparallel diodes of switches S_1 and S_2.

Fig. 4, *b* shows the simulation results for L_s=200 uH. It can be seen that the circulating current is significantly reduced, indicating that the introduction of additional inductance effectively suppresses circulating currents.



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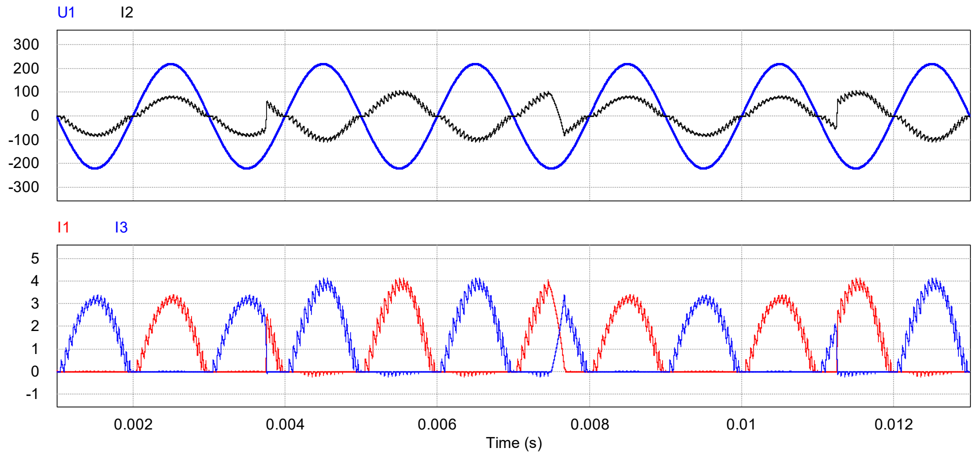
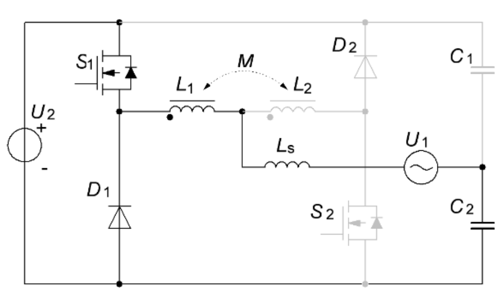


b

Fig. 4

During the interval when the AC current is positive, regardless of the polarity of the AC voltage, the active circuit consists of switch S_1, diode D_1, and inductors L_1 and L_s Fig. 5, *a*.



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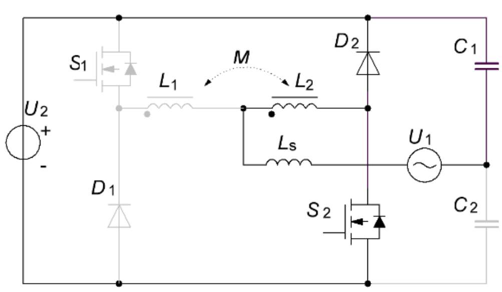

b

Fig. 5

Similarly, during the interval when the AC current is negative Fig. 5, *b*, regardless of the polarity of the AC voltage, the conduction path is formed by switch S_2, diode D_2, and inductors L_2 and L_s. In this case, the components associated with switch S_1, diode D_1, and inductor L_1 must not conduct current. Conversely, when switch S_1 is active, no current flows through inductor L_2.

As noted earlier, one of the main drawbacks of the asymmetric inverter with magnetically coupled inductors is the presence of circulating currents, which lead to additional power losses. Therefore, it is necessary to determine the parameter values or their relationships under which the circulating current can be significantly reduced. To this end, the formation of the positive half-cycle of the grid voltage is considered with switch S_1 in the active state. As shown in [23], under the adopted assumptions, when transistor S_1 is turned on, the circulating current through diode D_2 does not occur. In this case, the circulating current can only flow through the intrinsic body diode of switch S_2. To determine the conditions under which the circulating current approaches zero when switch S_1 is active, an equivalent circuit of the asymmetric inverter is constructed Fig. 6.

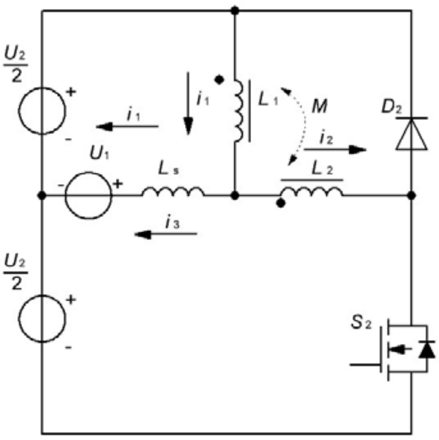

Fig. 6

A mathematical model of the converter was developed using the averaging method [24] to analyze the processes. Accordingly, the system of equations (1) in increments was formulated for the interval when switch S_1 is open, according to the equivalent circuit shown in Fig. 6.

$$\begin{cases} \dfrac{\Delta I_1}{T_i}\left(L_1+M\right)+\dfrac{\Delta I_3}{T_i}\left(L_S-M\right)=\dfrac{U_2}{2}-U_1, \\ \dfrac{\Delta I_3}{T_i}\left(L_S-M\right)-\dfrac{\Delta I_2}{T_i}\left(L_2+M\right)=-U_1-\dfrac{U_2}{2}, \\ \Delta I_2+\Delta I_3=\Delta I_1, \end{cases} \tag{1}$$

where T_{i} is the duration of the control pulse interval; $M=k\sqrt{L_1L_2}$ is the mutual inductance between the inductor windings; k is the magnetic coupling coefficient.

By solving the system of equations (1) with respect to the current increments and the duration of the second interval, the following expressions are obtained:

$$\Delta I_1=\frac{T_i}{2}\cdot\frac{U_2L_2-2U_1M-2U_1L_2+2L_SU_2-U_2M}{L_1L_S+2L_SM-M^2+L_1L_2+L_SL_2}, \tag{2}$$

$$\Delta I_2=\frac{T_2}{2}\cdot\frac{2L_sU_2-U_2M+U_1M+2L_1U_1+L_1U_2}{L_1L_S+2L_SM-M^2+L_1L_2+L_SL_2}, \tag{3}$$

$$\Delta I_3=\frac{T_2}{2}\cdot\frac{U_2L_2-2L_1U_1-L_1U_2-2U_1M-2U_1L_2}{L_1L_S+2L_SM-M^2+L_1L_2+L_SL_2}. \tag{4}$$

Consider the case of near-ideal magnetic coupling between the inductor windings, $M{\sim}L_1{=}L_2{=}L$. Under these conditions, the parameter relationships for which the current increment approaches zero within this interval can be determined. Expression (3) can be rewritten in a simplified form as follows:

$$\Delta I_2=\frac{T_i}{4}\cdot\frac{L_SU_2+2LU_1}{LL_3}. \tag{5}$$

By setting expression (5) equal to zero and taking into account the current direction, the required value of the additional inductance L_s is obtained, for which the increment of the circulating current approaches zero:

$$L_S=2L\left(U_1/U_2\right). \tag{6}$$

According to expression (6), as the doubled amplitude of the AC source voltage approaches the DC source voltage, the required value of the additional inductance L_s increases. Therefore, in the limiting case where twice the amplitude of the AC source voltage approaches the DC source voltage, the required value of the additional inductance L_s approaches the winding inductance of the magnetically coupled inductor. This indicates that, under such parameter ratios, the advantage of magnetic coupling in reducing the circulating current is significantly weakened, and minimization of the circulating currents requires an increase in the additional inductance.

As follows from the inverter structure Fig. 5, *b* and simulation results, when switch S_2 is active, diode D_1 does not conduct. Therefore, when condition (6) is satisfied, circulating currents in the inverter are eliminated.

To validate the obtained results, simulations were carried out. For purely active power transfer, two operating modes were considered: inverter mode, where voltage and current are in phase, and rectifier mode, where they are in anti-phase Fig. 7. The simulations were performed under condition (6).

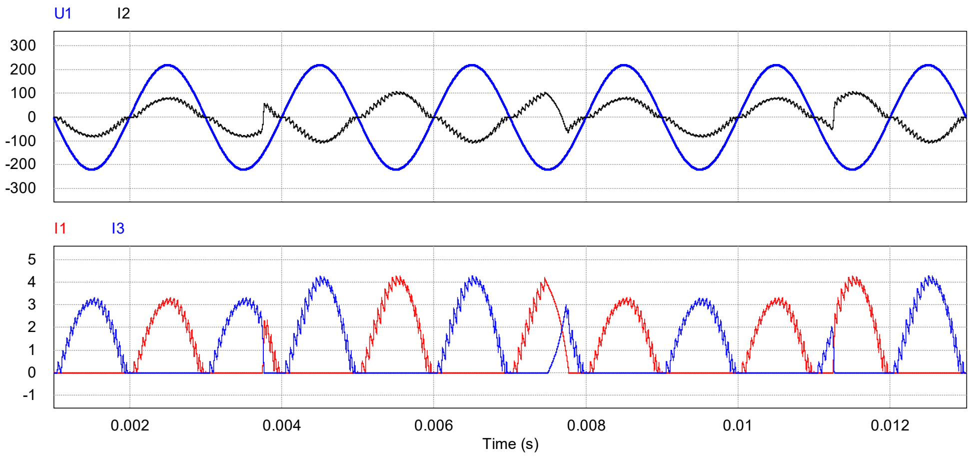

Fig. 7

Fig. 7 presents the simulation results of the inverter and rectifier operating modes of the asymmetric inverter under the condition L_s=L_1=L_2=2 uH. As observed from the results, the circulating current is eliminated.

The transfer of reactive power between the AC grid and the DC source introduces additional complexity in the control algorithm. Based on the analysis, it can be concluded that the leg consisting of S_1 and D_1 conducts positive current, while the leg formed by S_2 and D_2 conducts negative current, regardless of the voltage polarity.

For reactive power transfer, the phase shift between current and voltage must be within the range from 0 to 180°. Fig. 8 presents simulation results for two cases of reactive power transfer: capacitive mode Fig. 8, *a* and inductive mode Fig. 8, *b*.

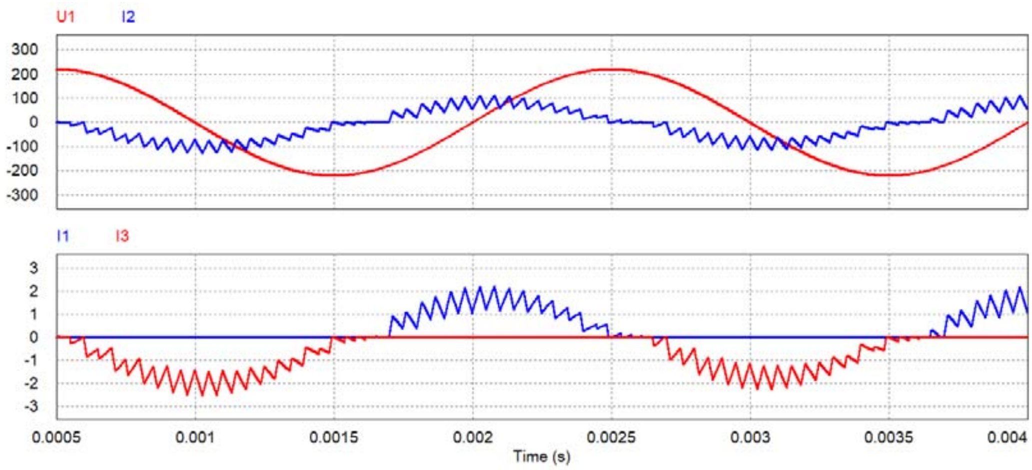

Fig. 8, *a*

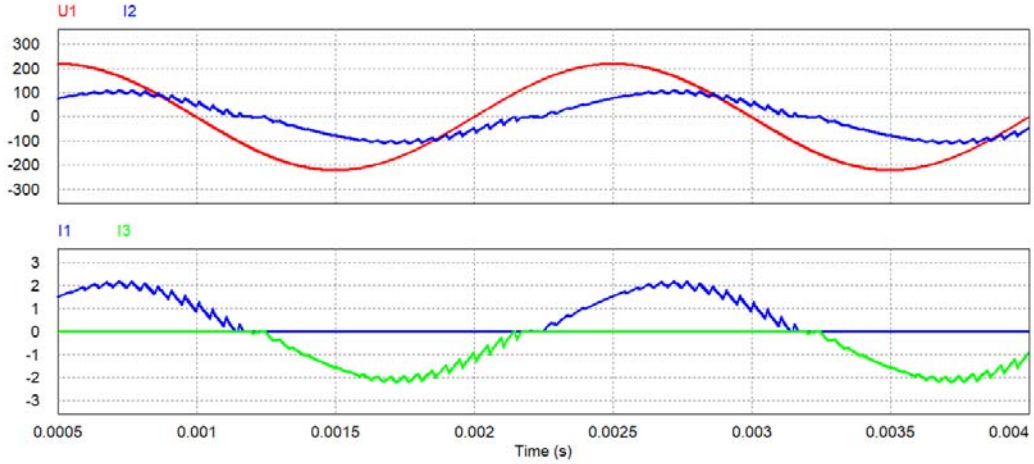

Fig. 8, *b*

As follows from the simulation results, when condition (6) is satisfied, circulating currents in the inverter are eliminated in all operating modes of the energy storage system based on the asymmetric inverter topology.

The conducted simulations confirm the validity of the obtained analytical results.

Conclusions. A new mathematical model was developed for calculating a bidirectional DC-AC converter based on an asymmetric inverter with magnetically coupled inductors and an additional inductance L_s, and recommendations for selecting its parameters were formulated. The obtained analytical relationships make it possible to determine, at the design stage, the inverter parameters that ensure an increase in its energy efficiency. A method is proposed for improving the structure of an asymmetric inverter by introducing additional inductance, which enables the elimination of unwanted circulating currents in the converter circuits. It has been established that, for a certain ratio of the parameters of the additional inductance and the voltages of the DC and AC sources, the circulating current in an asymmetric inverter with perfectly magnetically coupled inductors approaches zero. It is demonstrated that, as the difference between the DC source voltage and the magnitude value of the AC source voltage increases, the required value of the additional inductance decreases. The simulation results confirm the validity of the obtained analytical results and the effectiveness of the proposed approach.

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Conflict of Interest. The authors declare no conflict of interest.

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ДВОНАПРАВЛЕНИЙ DC-AC ПЕРЕТВОРЮВАЧ НА ОСНОВІ АСИМЕТРИЧНОГО ІНВЕРТОРА ДЛЯ ЗАСТОСУВАННЯ В ГІБРИДНИХ СИСТЕМАХ НАКОПИЧЕННЯ ЕНЕРГІЇ

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Роботу присвячено дослідженню та аналізу електромагнітних процесів у двонаправленому перетворювачі постійного струму в змінний на основі асиметричного інвертора з магнітопов'язаними дроселями, а також визначенню його параметрів з метою підвищення енергетичної ефективності. Для дослідження процесів використано метод усереднення в просторі станів та методи імітаційного моделювання. У результаті роботи отримано аналітичні вирази для розрахунку струмів в асиметричному інверторі з магнітопов'язаними дроселями на інтервалах комутації. Визначено взаємозв'язок між індуктивностями дроселів та параметрами вхідних і вихідних джерел електроживлення, за яких циркуляційні струми в колах інвертора відсутні, що забезпечує зниження статичних втрат потужності у перетворювачі. У ході досліджень отримано нові аналітичні та графічні залежності для роботи двонаправленого DC-AC перетворювача в режимах передачі активної та реактивної потужності, що розширюють попередні моделі асиметричних DC-DC перетворювачів. Отримані залежності дають можливість на етапі проєктування підвищити ефективність перетворювача шляхом зниження втрат потужності, зумовлених циркуляційними струмами, за рахунок вибору оптимального співвідношення параметрів інвертора. Бібл. 24, рис. 8.

Ключові слова: системи накопичення електроенергії, двонаправлений DC-AC перетворювач, асиметричний інвертор, високодинамічне двонаправлене перетворення електроенергії, гібридний електромобіль.

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