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STUDY OF A BIDIRECTIONAL CONVERTER USING AN ASYMMETRIC INVERTER WITH A MAGNETICALLY COUPLED TWO-WINDING INDUCTOR IN AN ENERGY STORAGE SYSTEM

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The electromagnetic processes in a bidirectional DC-DC converter using an asymmetric inverter in a battery energy storage system to manage energy flow between sources with different voltage levels are examined. The key advantages of bidirectional converters based on the asymmetric inverter topology are identified. The first advantage is the elimination of through-currents by avoiding the combinations of serially connected active power switches during switching intervals. The second advantage is the improved dynamic performance of power switches by using the external discrete diodes instead of internal diodes in the switches, significantly reducing the energy dissipated during the reverse recovery process. The article proposes the improvement of the asymmetric inverter structure with a magnetically coupled inductor for the bidirectional DC-DC converter through the addition of an extra inductor, which eliminates undesirable circulating currents in the converter that lead to power losses. Analytical expressions are derived for calculating the current increments during switching intervals in the magnetically coupled inductor. The relationship between its inductance and the parameters of the power sources without circulating currents is determined. References 16, figures 7.
Keywords: energy storage systems, bidirectional DC-DC converter, fast energy conversion, hybrid electric vehicle.

Introduction. The bidirectional DC-DC converters are key components in power supply and energy storage systems. The power supply systems under study, which are based on general construction principles, fundamentally differ from traditional systems because they feature the bidirectional energy flows [1]. Additionally, there is a large class of consumers requiring a regulated and stabilized DC voltage with the ability to reverse the current or voltage to ensure the efficient use of primary energy source. These consumers include electric drives (asynchronous, synchronous and brushless) and the systems that use them, such as the electric and hybrid vehicles [2].

The growing popularity of electric vehicles demands an increased attention to energy storage systems. The electric vehicles, in a traditional sense, rely on a battery as an energy source to ensure their operation. However, the autonomous battery integrated into an electric vehicle is not always sufficient to provide the necessary dynamics. For instance, to supply the initial peak power during the transient processes like starting, acceleration or sudden load changes, as well as to utilize the regenerative energy during braking, the additional energy storage system, such as a supercapacitor battery, is needed alongside with the main battery.

The most hybrid electric vehicle configurations use two energy storage devices: one with high energy capacity (the main battery) and the other device with high power and reversibility (an auxiliary supercapacitor battery). The main battery provides an extended driving range, while the auxiliary battery ensures the rapid acceleration and energy conservation during regenerative breaking [3].

The various topologies of bidirectional converters are employed to ensure the dynamic energy exchange between power sources, energy storage devices and loads. The new inverter structures, such as the dual buck inverter and the split-phase pulse width modulation (PWM) inverter have been proposed to en-

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hance the efficiency and reliability of inverters [4, 5]. These structures are widely used in various applications due to their lack of short-circuit issues and low losses during diode reverse recovery.

The study of bidirectional DC-DC converter topologies plays a crucial role in the rapid development of the hybrid vehicle industry. Many works have focused on investigating the bidirectional converters with effective power flow management [5–9]. Additionally, the various control strategies have been explored to improve the quality of power flow. In this study, we address to the elimination of certain drawbacks associated with the using an asymmetric inverter as a high-power bidirectional DC-DC converter, particularly under challenging conditions with short conversion periods, for use in hybrid automotive power systems.

The objective of the study is to investigate the electromagnetic processes in a bidirectional DC-DC converter using an asymmetric inverter in energy storage systems, focusing on the changes in energy flow direction during dynamic transient modes. Additionally, the goal is to determine the conditions under which the circulating currents take place, as well as their magnitude, depending on the parameters of the converter and magnetically coupled inductor**.**

Methods. A well-known structure of a bidirectional converter is based on basic DC converters [1, 2], such as buck and boost converters (and their derivatives). These converters can be used independently to enable the bidirectional energy flow; however, in this case, the electromagnetic components and power switches are used inefficiently. Nevertheless, unidirectional DC-DC converters can be represented as bidirectional converters based on the half-bridge inverter topology by utilizing the built-in internal diodes of the controlled switches and the shared use of inductor. It is important to note the several drawbacks of this configuration, i.e. excessive energy losses during diode reverse recovery or failure when both switches are accidentally turned on, that can lead to device malfunction. The traditional solution to this problem is to introduce a pause in the switching interval, which partially results in a loss of duty cycle duration and limits the switching frequency. Additionally, the shared inductor, which is used for smoothing current ripple, degrades the dynamics of transient processes when the direction of energy flow changes, that is a significant disadvantage for hybrid energy systems. This reduces the amount of saved energy, for example, during the transition to regenerative braking mode [2].

One of the ways to solve the above issues is to develop a bidirectional buck-boost DC converter using an asymmetric inverter with a magnetically coupled inductor (Fig. 1) [2, 4]. The device is a single-phase inverter that contains four switches, with switches VT1 and VT2 being controllable. This converter topology allows the operation in both buck and boost modes, in both directions of energy flow. When transferring the energy from source U2 to U1, switch VT1 is controlled, while VT2 is off. When transferring the energy in the opposite direction, from source U1 to U2, the situation is reversed, with VT2 being the controlled switch.

The converter exhibits two key advantages: firstly, the through-currents are eliminated because no active power switches are connected in series in each phase leg; second, the energy dissipation during the reverse recovery of power switch is significantly reduced, as the discrete diodes, which have much better dynamic properties than the internal diodes of power switches, can be used.

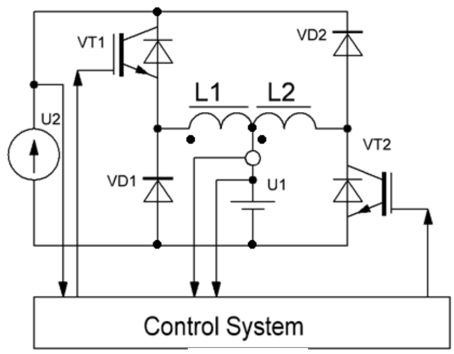

Fig. 1

The solution using the asymmetric inverter with magnetically coupled inductor effectively copes with the above problems as it eliminates the switching loss issues [4]. The half-bridge inverter topology based on the asymmetric inverter with a magnetically coupled inductor is advantageous due to its simplicity and easy control. Currently, the various modifications of this topology with different control strategies have been developed and studied [5–9].

Despite these advantages, the converter has some drawbacks when using a magnetically coupled inductor, especially when the voltage levels on the low-voltage and high-voltage sides differ significantly. In such cases, the circulating currents can occur in certain operating modes of the converter [2], resulting in power losses. Some studies propose the using an inductor without magnetic coupling to prevent the circulating currents [10–12], but this solution loses one of the main benefits of using the asymmetric inverter that is the fast transition dynamics between energy storage and energy release modes. Other works suggest using the opposing switching of inductor windings and complex additional filtering systems [13, 14].

It was shown in [2] that there are no circulating currents in a bidirectional converter, when the supply voltage on the low-voltage side is half of the voltage on the high-voltage side and the current in the inductor is continuous. However, in practical energy storage systems or bidirectional converters, the voltage on the low-voltage source (battery) usually differs by more than twice than the voltage on the high-voltage side. In this case, with magnetic coupling in the inductor, the circulating currents occur. The issue of circulating currents has not yet been fully solved in this article. This work proposes a solution to minimize the circulating currents for power losses reducing and improving the overall efficiency of energy conversion.

It is known that there is no circulating current in an asymmetric inverter with non-magnetically coupled inductors [9], but this leads to slow transient processes when the direction of energy flow changes. The use of inverter structure with magnetically coupled inductors ensures a good responsiveness during changes in the direction of energy flow. However, under certain ratios of the power source parameters on the low-voltage and high-voltage sides [2], the circulating currents can occur [14]. Thus, the strong magnetic coupling in the inductor leads to circulating currents, while non-availability of magnetic coupling prevents them. In this study, we aim to optimize the parameters of the magnetic coupling in a dual-winding inductor to maintain a good dynamic performance and minimize the circulating current.

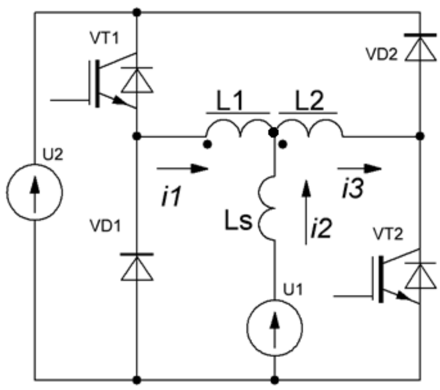

Fig. 2

The study of the asymmetric inverter with a magnetically coupled inductor was conducted by calculating the operating modes of the converter using PSIM simulation software based on a developed model (Fig. 2) with magnetically coupled inductors, where L_1=L_2=30 μH, and the additional inductor (L_s=6 μH) was added to block the unwanted circulating currents. It is assumed that the switching elements in the converter are switched instantaneously, their on-state resistance is zero, and the active-resistance of inductor windings is also zero. In Fig. 2, the power source $U2 > 2U1$.

Fig. 3 presents the calculated currents $i_1(t)$, $i_2(t)$, $i_3(t)$, for the operation of bidirectional converter in discontinuous current mode.

When the energy is transferred from source $U2$ to source $U1$, the converter operates in buck mode with active transistor VT1. During the accumulation phase, while transistor VT1 is on, voltage $U2$ is applied to magnetically coupled inductors L_1=L_2. Since the windings are magnetically coupled, the voltage at the connection point of inductor Ls is greater than $U1$, that causes the circulating current flowing through the diode of transistor VT2 and inductor winding L_2. This results in increased static losses due to the current flowing through the antiparallel diode of transistor VT2. When the transistor is turned off, the circulating current disappears (Fig. 3). Therefore, if the antiparallel diode in transistor VT2 is blocked, the circulating current would not occur. However, this would result in additional static losses in the converter.

When the energy is transferred from source $U1$ to source $U2$, the converter operates in boost mode with transistor VT2. When VT2 is turned on, the voltage from source $U1$ is applied to the half-winding of inductor L_2. Since the voltage across the magnetically coupled windings is less than $U2$, there is no circulating current. However, when VT2 is turned off (Fig. 3), the circulating current flows through diode VD1 and the half-winding L_1 of inductor, because the magnetically coupled winding induces voltage $U2/2>U1$ across L_1. The occurrence of circulating current $i_1(t)$ (Fig. 3) means that not all the energy accumulated in L_2 during the on state of transistor VD2 is transferred to source $U2$.

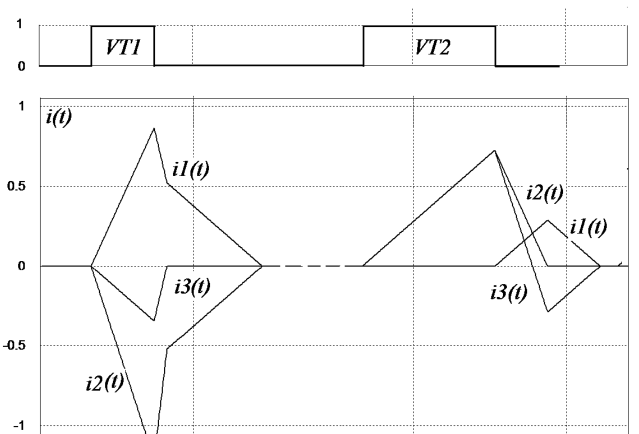

Fig. 3

As shown by simulation (Fig. 4), during the operation of the inverter in boost converter mode with intermittent inductor currents, the four intervals of structural constancy can be identified (Fig. 5): the first interval occurs when transistor VT2 of the converter is on (time interval t_0-t_1) while all other switches are closed. The subsequent intervals during the off times of transistor VT2 are following: the second interval is t_1-t_2, then the third interval is t_2-t_3, and the fourth range is t_3-T. The availability of these three intervals during the off periods of the transistor is influenced by the magnetic coupling of the inductor windings and the voltages at power sources.

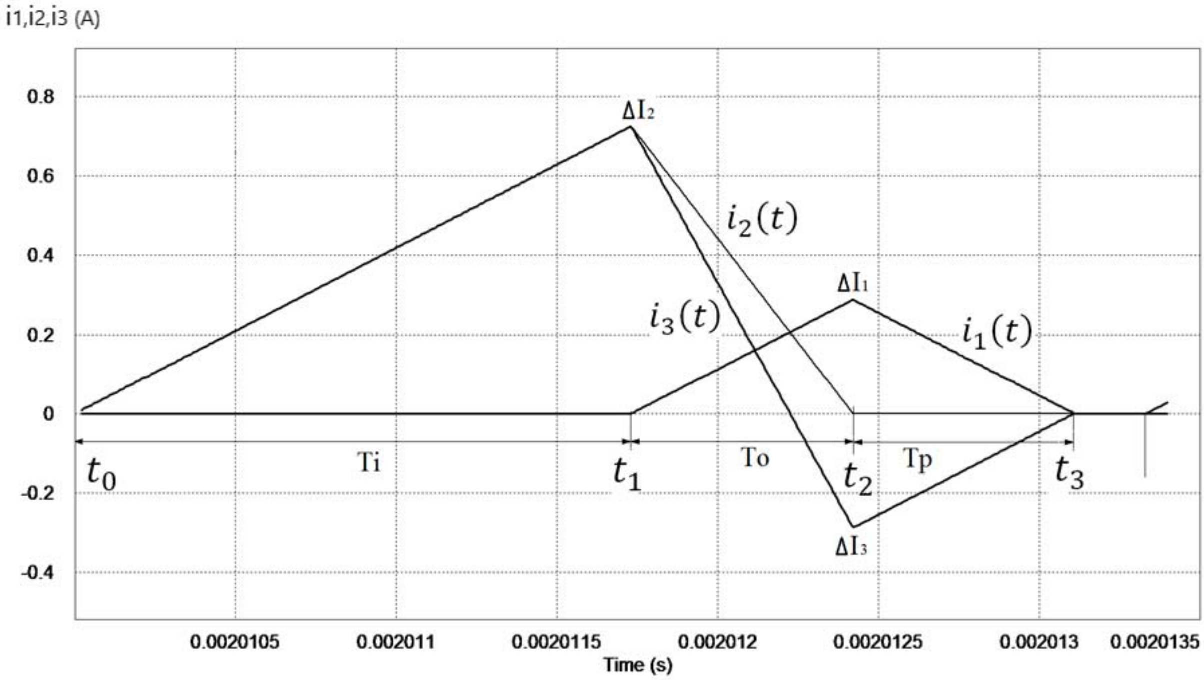

Fig. 4

This work examines the operation of converter in the mode of energy transfer from low-voltage source to high-voltage one. The equivalent circuit configurations for the time intervals of interest T_i and T_o (Fig. 4) are shown in Fig. 5, when transistor VT2 is on, and in Fig. 6 during the time interval T_o after the transistor VT2 is turned off, when the current $i_2(t)$ goes to zero. Let us determine the parameters of equivalent circuits in which the circulating currents are not significant.

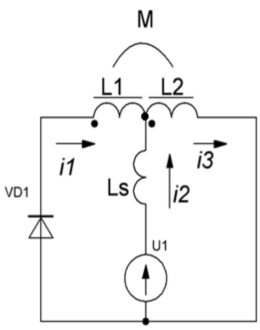

Fig. 5

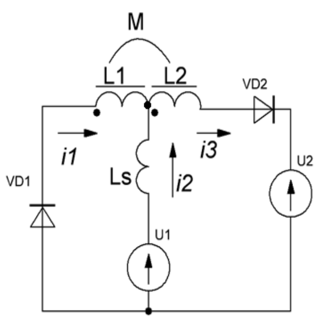

Fig. 6

The analysis of time diagrams in Fig. 4 indicates that the waveform of the converter's state variables, i.e. currents i_1, i_2, i_3 exhibits the multi-step behavior with several sequential stages of increase and decrease. Notably that current i_3 even has a reversal of sign.

To analyze these processes, we will use the converter model obtained through the averaging method developed in [15, 16]. Accordingly, we will present the system of differential equations for the first two intervals, where the first equation corresponds to the equivalent circuit shown in Fig. 5, and the subsequent equations correspond to the equivalent circuit in Fig. 6. For the second interval, we will take into account the fact that under steady-state operation, the increment in the current of inductor L_2 is equal to the sum of the increments in the currents $\Delta I_1+\Delta I_2=\Delta I_3$ of inductors L_1 and L_s:

$$\begin{cases} L_2\dfrac{\Delta I_2}{T_i}+L_s\dfrac{\Delta I_2}{T_i}=U_1, \\ -L_1\dfrac{\Delta I_1}{T_o}+M\dfrac{\Delta I_2}{T_o}-L_s\dfrac{\Delta I_2}{T_o}=U_1, \\ U_1+L_s\dfrac{\Delta I_2}{T_o}+L_2\dfrac{\Delta I_2}{T_o}-M\dfrac{\Delta I_1}{T_o}=U_2, \\ \Delta I1+\Delta I2=\Delta I_3, \end{cases} \qquad (1)$$

where T_i is the given pulse duration; T_o is the duration of the second interval; $M = K\sqrt{L1L2}$ is the mutual inductance between inductor windings; K is the magnetic coupling coefficient.

By solving the system of equations for current increments and the duration of the second interval, we obtain:

$$\Delta I_1 = -\frac{T_i U_1^2 (L_2 + M) + (L_s - M) T_i U_1 U_2}{L_s^2 U_2 + ((U_2 - U_1) L_1 - M U_1)(L_2 + L_s) + L_2 L_s U_2}, \quad (2)$$

$$\Delta I_2 = T_i \frac{U_1}{L_2 + L_s}, \quad (3)$$

$$\Delta I_3 = \frac{(L_1 + L_2 + 2M) T_i U_1^2 - (M + L_1) T_i U_1 U_2}{(L_s + L_2)(L_s U_2 + (L_1 U_2 - M U_1 - L_1 U_1))}, \quad (4)$$

$$T_o = \frac{((2L_s - M)M + (L_1 L_2 + L_1 L_s + L_2 L_s)) T_i U_1}{(L_s + L_2)(L_s U_2 + (U_2 - U_1) L_1 - M U_1)}. \quad (5)$$

Considering the case close to ideal magnetic coupling between the half-windings of inductor $M \approx L_1 = L_2 = L$, we can find the parameter relationships, for which the current increment ΔI_1 will tend to zero within the second interval, by simplifying expression (2) as follows:

$$\Delta I_1 = -\frac{T_i U_1 (2LU_1 + (L_s - L) U_2)}{L_s^2 U_2 + (U_2 - 2U_1) L^2 + 2LL_s (U_2 - U_1)}. \quad (6)$$

By setting expression (6) to zero, we can determine the value of additional inductance L_s at which the increment in circulating current tends to zero:

$$L_s = L \frac{U_2 - 2U_1}{U_2}. \quad (7)$$

Fig. 7 shows the simulation results for the bidirectional converter based on asymmetric inverter circuit with the following parameters: L_1=L_2=30 μH, PWM frequency of 30 kHz and power sources U_1=14 V and U_2=38 V. According to expression (7), the value of additional inductance is L_s =7,89 μH.

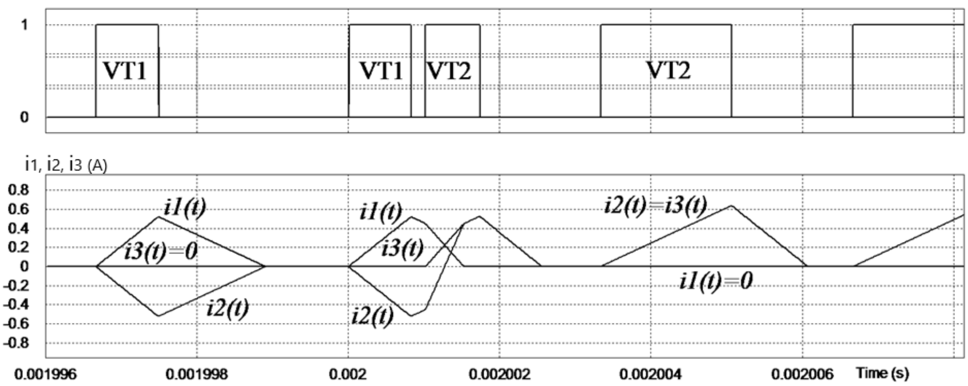

Fig. 7

The simulation results show that there are no circulating currents. Despite the use of additional inductance (inductor), a high energy transfer speed is maintained when the direction of energy transfer changes Thus, the study has determined the relationship between the key parameters of the asymmetric inverter with additional inductance to prevent the circulating currents in ideal magnetically coupled two-winding inductor.

Conclusions. The analytical expressions have been derived for determining the parameters of the additional inductor when using the asymmetric inverter structure based on the ratio of the low-side and high-side power sources and the parameters of the two-winding power inductor with nearly ideal magnetic coupling. These findings prevent the circulating currents in converter. The simulation confirms the validity of the results obtained.

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ДОСЛІДЖЕННЯ ДВОНАПРАВЛЕНОГО ПЕРЕТВОРЮВАЧА З ВИКОРИСТАННЯМ АСИМЕТРИЧНОГО ІНВЕРТОРА З МАГНІТОЗВ'ЯЗАНИМ ДВООБМОТКОВИМ ДРОСЕЛЕМ В СИСТЕМАХ НАКОПИЧЕННЯ ЕНЕРГІЇ

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Розглянуто електромагнітні процеси у двонаправленому перетворювачі постійного струму під час використання асиметричного інвертора в акумуляторній системі енергонакопичення задля керування потоком енергії між джерелами з різним рівнем напруги. Визначено основні переваги двонаправлених перетворювачів на основі топології асиметричного інвертора. Перша перевага полягає у відсутності наскрізних струмів завдяки усунен-

ню комбінацій послідовного з'єднання активних силових ключів на інтервалах комутації. Друга перевага полягає в покращенні динамічних властивостей силових ключів за рахунок використання зовнішніх дискретних діодів замість внутрішніх в силових ключах, що дає змогу значно зменшити енергію, яка розсіюється в процесі зворотного відновлення силового ключа. У роботі запропоновано шлях вдосконалення структури асиметричного інвертора з магнітопов'язаним дроселем для двонаправленого перетворювача постійного струму за допомогою додаткового дроселя, який усуває небажані циркуляційні струми у перетворювачі, що призводять до втрат потужності. Отримано аналітичні вирази для розрахунків приростів струмів на інтервалах комутації у магнітопов'язаному дроселі та визначено взаємозв'язок між його індуктивністю та параметрами джерел електроживлення, за яких циркуляційні струми відсутні. Бібл. 16, рис. 7.
Ключові слова: системи накопичення електроенергії, двонаправлений перетворювач постійної напруги, швидке перетворення енергії, гібридний електромобіль.

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