MULTI-INPUT BIDIRECTIONAL DC-DC CONVERTERS FOR SHIP ELECTRICAL SYSTEM: A REVIEW

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ABSTRACT
A multi input converter topology are combination of DC to DC converters which are used improve the reliability, flexibility and efficiency of the overall system through the structure of the converter and to achieve better monitoring on the energy management resources. Therefore multi-input dc-dc converters will be of particular interest of a lot of applications such as micro grid, energy storage system, hybrid power system, electric and hybrid electric vehicles, satellite system, etc. Different topologies have been proposed to combine different types of renewable energy sources as diversion increase the utilization of renewable energy sources such as photovoltaic panels which have the advantage of dc current and voltage characteristics and can be integrated through multi-input DC-DC converters. There are two categories for MI topologies: non-isolated and isolated, the non-isolated topologies are based on electrically connected circuit (ECC) and the isolated topologies are based on magnetically connected circuit (MCC). This paper reviews developments and new trends happening in the area of multi input controllers (MIC) which can be of use in a hybrid ship electrical system. Various types of MIC’s are studied. Various types of isolated and non-isolated topologies are discussed.

Keywords: Multi input converters, Renewable energy sources, Hybrid system, Isolated and Non-isolated topologies.

I. INTRODUCTION
Power electronics converters are a key enabler for modern electric ships [1]. Power converters converts the alternating current (ac) power produced by generators at fixed voltage and frequency to ac powers at various voltage level and frequency. The direct current (dc) at various voltage levels is needed for supplying and controlling propulsion motors, ship service loads, mission loads and distribution buses. These converters need to have high efficiency and reliability and also should meet the performance requirement. For shipboard systems, power converters should also be of a smaller size, light weight and have high-power density to save space and fuel. The increasing loads demands for a better converter capability, higher efficiency and power density without increasing the ship size.

To meet with laws of MARPOL (The International Convention for Prevention of Marine Pollution For Ships), the emission of greenhouse gases is to be reduced to a considerable extent by reducing the use of fossil fuel. Addition of renewable sources to ship electrical system helps in reducing the emission of the harmful gases. Recent development and trends in the electric power consumption indicate an increasing use of renewable energy. Renewable energy sources are distributed throughout the world in such a way that, every region has a renewable energy resources of one type or another [2]. In photovoltaic (PV) or wind power generation system, a power converter is required to extract maximum power and to provide a desired output. In literature [3]-[5] PV converters are presented while wind power converters are discussed in [6]-[8]. A Single renewable source will not be enough to meet the energy requirements as it keeps varying with the climatic conditions. Thus, there is a need for addition of multiple energy sources [9]. The main challenge in renewable source energy system is the power fluctuation. Integrating fluctuating renewable sources to ships electrical system increase the difficulty to stabilizing the power flow and load sharing. Energy storage system (ESS) is a great solution to improve the system reliability, smooth the power fluctuations and load leveling [6]-[8].

The conventional method uses an individual power electronic converter for each of the sources which integrated into a common dc bus [10]. The complexity of individual sources and the greater number of components makes the system costly and complex. The synchronization among the sources is also
difficult [10]-[14]. To overcome these drawbacks, power electronic converters, termed as multi-input converters (MIC) are used. In these converter structures, multiple energy sources like conventional energy sources and renewable energy sources are combined, which are then connected to a common dc bus through a single converter [13]. The advantages of these MIC are simple structure, a smaller number of conversion stages and less device count with high control flexibility. This made these structures suitable for applications like hybrid energy systems with and without energy storage, electric/hybrid vehicles, grid, and standalone systems, satellite and aerospace applications and uninterrupted power supplies [14]-[17]. Multi-input bidirectional DC-DC converters can accept inputs from different dc sources which can be unidirectional or bi-directional. A bi-directional converter can be used in case of an energy storage system. The output of the multi-input bidirectional DC-DC converter can be connected directly to the DC load. It can be connected to an AC bus using an inverter. Many three-port and four-port bidirectional converters, which can satisfy various requirements are discussed. These converters can be categorized into three types: non-isolated converters, partly-isolated converters, and isolated converters [9].

Following the recent wave of interest in research on the multi-input converters (MICs), this paper made a comprehensive review of the bidirectional MICs to expand its application in the ship electrical system.

II. CATEGORIES OF MULTI-INPUT BIDIRECTIONAL CONVERTERS

Multi-input bidirectional converters can be categorized into three types: non-isolated, partly-isolated, and isolated converters. Non-isolated converters are used where the galvanic insulation is not required. This is because all the ports are connected directly. Most of these converter topologies are based on the traditional boost, buck, and buck-boost converters. Since the voltage conversion ratio depends on the duty cycle, these converters have a limited voltage gain. Partly-isolated converters have the input ports which includes the bidirectional ports connected directly. These ports are then connected to the output port with a galvanic isolation by a high frequency transformer. There are also other partly-isolated converters that have an output port and a bidirectional port which is connected without any galvanic isolation. These ports are then connected to the input port through a high frequency transformer. In isolated converters, the power flow between any of the multi-ports is through a multiple winding high-frequency transformer. These types of converters have good galvanic isolation and all of ports have their own components. Most of the isolated converter topologies are based on the full-bridge converters or half-bridge converters or the combination of them. In both partly isolated and isolated converters higher voltage conversion ratios can be easily achieved by selecting appropriate number of turns winding of the high frequency transformer. The use of high frequency transformer will increase the converter size and therefore reduces power density and system efficiency.

a) Family of Multiport Bidirectional DC-DC Converters

A family of multiproduct bidirectional DC–DC converters derived from a general topology is presented in [15]. Six topologies has been presented with different combinations of switching cells and interconnecting methods which includes all the three types: non-isolated, partly-isolated and isolated topologies. The combination of DC-link and magnetic coupling methods shown in this topology integrates multiple energy sources. In DC-link method, a number of different sources are interconnected together through switching cells to a DC bus by means of capacitors. But, the limitation is that the DC-link cannot handle a wide range of source voltages. Therefore, the operating voltages of different sources should be in a particular range to avoid large buck/boost conversion ratios. In the magnetic-coupling method sources are interconnected through a multi-winding transformer. Thus multiple sources with different voltage levels can be connected. Also the sources are isolated, which could be a mandatory requirement for safety reasons in many of the applications. This model makes use of both DC-link and magnetic coupling methods to combine multiple sources without using additional switches. Figure 1 shows the general topology, where the system has N different DC buses (i.e. DC bus 1, DC bus 2,..., DC bus N) [1].
Figure 1: General topology with combination of DC-link and magnetic-coupling for multiport bidirectional DC-DC converters

Different structures of the basic switching cells are shown in Figure 2. The cells used in the general topology are the canonical switching cell, boost-half-bridge cell, half-bridge cell and full bridge cell. In these converters, there is only one source directly coupled to the DC bus, which is connected through transformer winding. The full bridge is used in the case where there is only one source coupled to the winding and the operation mode is square wave. The full bridge and the half bridge converters are can be interchanged by adding or removing two switches. The use of the boost-half-bridge in the system plays a key role in combining the DC link with magnetic coupling. It makes the converter more compact, resulting in fewer power devices.

Figure 2a: Canonical switching cell
Figure 2b: Boost half bridge
The system is open to the addition of more sources through DC buses or transformer windings. The method of integrating a source to the system by the DC-link or magnetic coupling depends on the isolation requirements and the operating voltage. To illustrate possible realisations of this multiport bidirectional converter topology, a set of three-port converters derived from the general topology are discussed. As an example in figure 3, a typical fuel cell generation system is studied which is a three-port structure which has a fuel cell, load and storage. To interconnect these three ports, a three port converter can be used. There are a number of ways to construct such type of a converter [15].

Figure 4 shows a magnetically coupled three-port converter (the triple-active-bridge converter) [13, 17]. The half bridges can be interchanged to full bridges. In addition to galvanic isolation, this converter provides voltage matching at different port levels. This can be done just by choosing the required number of turns for the windings. The resulting leakage inductances will be the part of the circuit like energy transfer elements.

A converter which combines a DC-link and a magnetic coupling is shown in figure 5 [15]. In this converter, a fuel cell and the storage are connected through a DC bus because they have nearly equal operating voltages, and the load is connected through a transformer winding. Six switches are used in the system and all the three ports are bidirectional. This system is suitable for applications in which the low operating voltage of the fuel cell and storage is to be boosted to match the high voltage at load-side, which then feeds an inverter to generate an AC output.

In addition to the converter in figure 5, figure 6 shows the possibility of coupling the storage directly to the DC-bus, which is a compact and simpler topology. In this case, only four switches are needed. But, the performance of this converter may not be as efficient as the converter of figure 5 because the DC-bus voltage (i.e. the terminal voltage of the storage) should not vary over a wide range. [13]

Figure 7 illustrates a further possibility to use the boost half-bridge in order to realise a current-fed port for a storage device or fuel cell. This configuration minimises the current ripple of the port. As this is a variant of the converter shown in figure 7, the other two ports could also use the boost-half-bridge instead of the half bridge, as shown in figure 8, especially for applications in which the current ripple of the fuel cell and/or storage is to be strictly limited. [17]
Figure 4: Magnetically coupled three-port converter - topology 2

Figure 5: Three port converter combining DC-link and magnetic coupling - topology 3

Figure 6: Three-port converter with storage directly coupled to DC-bus - topology 4

Figure 7: Magnetically coupled three-port converter with one current-fed port - topology 5

Figure 8: Magnetically coupled three-port converter with two current-fed ports - topology 6
b) Non-Isolated Multi-Input Bidirectional Converters

Different types of non-isolated three-port DC–DC converters are discussed in the literature with different types of control and modulation methods. Some of them use only one inductor resulting in compact converter size and there is further improvement of the power density because other topology mostly uses two or three inductors. Since most of these converters are derived from the basic boost, buck, and buck-boost converters, the gain value of these converters are limited. To overcome this limitation, some three-port DC–DC converters use coupled-inductors which helps to extend the voltage conversion ratio.

A new dc-dc converter with buck-boost capability is proposed in [16] which is suitable for application with systems consisting of renewable energy sources. This converter can deliver a desired output voltage for a wide range of input voltage variations. The converter can act as a buck-boost converter depending on the load variations by changing duty cycle of the switches. The converter switches turn on and turn off at the same time which makes the control system of the proposed converter much simpler.

![Figure 9: Proposed Converter in [16]](image)

In [17] three-port DC-DC converter is proposed which interface a photovoltaic (PV) system, a battery system and a DC load. The first part of the proposed is converter inserted between the PV system and the DC load is a new derivation of the SEPIC converter which can step up the PV output voltage which is not possible in the basic SEPIC converter. Similarly the proposed converter in 16, can reach high step-up gains under lower duty ratios leading to lower conduction losses and hence higher efficiency. The second part of the proposed converter is a combination of buck and boost converter which can be used for charging and discharging of the battery.

![Figure 10: Proposed three port converter in [17]](image)

The proposed converter [18] has a large voltage gain at a small duty ratio which is lower than 0.5. This low duty ratio reduces the electromagnetic interference, reverse recovery problem. The converter does not involve any transformer to increase the voltage, eliminating any voltage spike across the power electronic switches and reducing the converter size. All the switches in this converter operate depending upon a single control signal which reduces the control complexity. Therefore, the proposed converter can contribute a lot to the renewable energy applications where a large dc-dc voltage transformation is needed.
In [19], a non-isolated three-port converter is studied for a photovoltaic (PV)-battery hybrid power system application. A bidirectional Buck/Boost converter and a semi-active full-bridge rectifier are connected in a stack configuration to provide three power ports which are a PV input port, a battery storage port and an output load port. Partial input power is transferred through the transformer, while the rest is transmitted through the direct path of power from input side to the load, which would reduce the losses of transformer. Thus a compact construction and higher efficiency can be achieved. The output voltage of the converter is regulated using phase-shift control, while the maximum power point tracking control of solar photovoltaic and the battery charging control are realized by pulse width modulation.

A high step up non isolated DC-DC converter with extendable topology is proposed [20]. This converter is symmetric, extendable and consists of m+n+ 2 Active Passive Inductor Cell (APIC). This provides a high voltage gain with low voltage stress on the switches. To verify theoretical analysis, simulation of proposed structure was done which converts a 20 V input voltage to 400V output.

c) Partly-Isolated Multi-Input Bidirectional Converters

In [21] a four port dc-dc converter, shown in Figure 12, is proposed with two photovoltaic sources and energy storage element together with the load. The phase-shifting control eliminates the circulating current and thereby reduces conduction loss and current ripple in the input ports. The power transfer capability from PV is also increased.

The proposed converter in [22], which is shown in Figure 13, is a bi-directional partly isolated four port DC-DC converter, combined by two boost converters and a bidirectional full-bridge DC-DC converter. A variable step size conductivity incremental method for PV unit MPPT control is used. The control of bidirectional full-bridge DC-DC converter is divided into two types which are DC transformer control and the phase shift control. It can obtain a voltage gain which is higher and it reduces power consumption and ports current ripple. In addition, it can be operated with soft switching on the switches using appropriate control and modulation methods.
Based on traditional half-bridge topology a four-port dc-dc converter is proposed in [23] as shown in Figure 14. Two switches and two diodes are added to the half-bridge topology. The topology has four power ports: one bidirectional storage port, two RES sources and one isolated port for the load. For higher efficiency zero-voltage switching (ZVS) is achieved for all the main switches. Three port of the four ports are regulated and the fourth port is unregulated to which is used to maintain the power balance of the system.

A four-port bidirectional dc-dc converter to interface a PV panel, wind turbine generator (WTG), and battery to a DC micro grid system, which is shown in Figure 15, is proposed in [25]. WTG, PV panel and battery are connected to Port 1, Port 2 and Port 4 respectively consisting of half-bridge switching cells. These input ports are connected to the primary side of the high-frequency transformer and the output port, i.e., Port 4 is connected to the secondary side and is linked to DC micro grid. In this topology the battery is charged from RES only. A modified topology of [25], which is shown in Figure 16, is proposed in [26]. It is possible to charge the battery from both RESs and the DC micro grid, so the power flow can be managed in both standalone mode and grid-connected mode.
A number of isolated multiport converters have been proposed for renewable energy integration systems. The topologies include full-bridge converter [7]-[8] and half-bridge converter [6], [9], which can achieve high efficiency because they can be soft-switched when phase-shifting technical is used. However, the aforementioned multiport converters are three-port (or tri-port) and cannot be directly used when more than three energy sources are used. Furthermore, the battery in those three-port converters can only be charged by the energy sources but cannot be charged by the grid side, i.e., the battery can only provide the deficient power to the micro grid but cannot absorb the surplus power, which makes it impossible to participate the power management at the micro grid system level. Therefore, for those applications where three energy sources are used, e.g., to interface a PV panel, a WTG, and battery to the grid, a four-port converter with bidirectional power direction between the micro grid and the battery is desired.

d) Isolated Multi-Input Bidirectional Converters

An isolated multiport bidirectional dual active bridge DC-DC Converter to be used in fast charging applications is proposed in [27] which is shown in Figure 17. The topology uses four full-bridge sections connected through high frequency (HF) transformer, the first port is connected to PV source, the second port is connected to ESS and can operate in charging and discharging mode, the remaining two ports connected in the secondary of HF transformer are connected to two different loads.
With a high-frequency three-winding transformer and three half-bridges a three-port triple-half-bridge bidirectional dc-dc converter topology is proposed in [28] as shown in Figure 18. One of the half-bridges is a boost half-bridge interfacing a power port with a wide operating voltage. Port 1 is connected with the primary source, i.e. fuel cell, Port 2 is connected to the load and Port 3 is for storage system in this case it is a super capacitor. All the three ports are coupled with a high frequency transformer. Phase shift in combination with PWM controls the system where the Phase shift control achieves the primary power flow control.

This [29] paper proposes a new four-port-integrated dc/dc topology, which is suitable for various renewable energy harvesting applications. An application interfacing hybrid photovoltaic (PV) and wind sources, one bidirectional battery port, and an isolated output port is given as a design. It can achieve maximum power-point tracking (MPPT) for both PV and wind power simultaneously while maintaining a regulated output voltage. A soft switching boost converter uses a simple auxiliary resonant circuit, which is composed of an auxiliary switch, a diode, a resonant inductor and a resonant capacitor. All switches in the adopted circuit perform zero-current switching by the resonant inductor at turn on, and zero-voltage switching by the resonant capacitor at turn-off. This switching pattern can reduce the switching losses, voltage and current stress of the switching device.

III. COMPARISON OF MULTI-INPUT BIDIRECTIONAL CONVERTERS

Apart from the cost of the control circuits, the non-isolated three-port converters generally result in lower cost than the partly-isolated and isolated converters and usually use less power switching devices and require a fewer components. Also, the need to use a high-frequency transformer can further increase the cost of the partly isolated and isolated three-port converters. Among the non-isolated converters, the topologies with high voltage gain are more costly than the other converters due to the use of a coupled-inductor.

Reliability is an important factor to evaluate the performance of the converters [63, 64]. For the converters, the reliability will decrease with increase in operation time. It is also understood that more switches the converter uses; the lower is the reliability the converter. Therefore, the non-isolated and partly-isolated converters have relatively higher reliability than the isolated converters.

Although all of the reviewed three-port converters are capable of the function of MPPT control, and even though they can provide the required load demand with the help of the energy storage system, there are
limitations to the application of these converters due to their unique configuration. The non-isolated converters can be preferred for small power applications such as portable products. They cannot be used for applications that require galvanic isolation, where partly-isolated and isolated three-port converters are better choices.

IV. CONCLUSION

Power converters are of major importance in ship electric system. For a hybrid system with more than one energy source, a multi input converter is necessary for efficient, compact, reliable, light weight hence high-power density to save space and fuel. Various types of multi input DC-DC converter topologies are discussed which can be of use in a hybrid ship electrical system. From the review we can conclude that an isolated bi-directional multi input converter will be suitable for a hybrid ship electrical system. In future, more research can be conducted in designing a suitable hybrid electrical system with multi-input dc-dc converter for the application in ship. This paper might help the researchers to have an overall view and basic knowledge about the various topologies of multi-input dc-dc converters.

V. REFERENCES


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