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SURVEY

Advancement in Converter Topology, Control, and Power Management: Magnetic Linked Power Converter for Emerging Applications

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ABSTRACT The magnetic linked converter plays a significant role in the power electronics industry due to its merits of being flexible to control, the high efficiency of power transmission, the performance of galvanic isolation, etc. These features make magnetic linked converter a prominent candidate for an effective interface for renewable energy integration to the traditional power grid, more electric aircraft applications, electric vehicle charging implementation, etc. The traditional controller of the magnetic linked converter is the linear control method which cannot ensure smooth bidirectional power routing and a high level of decoupling especially for the electric vehicle charging application. In the worst-case scenario, the traditional controllers can be fully saturated and cause severe system-wide unbalancing issues. Recently, the magnetic linked converter technology with advanced control decisions has been adopted for the electric vehicle charging application. The magnetic linked converter technology for electric vehicle charging applications provides a higher degree of control flexibility to supply multiple loads simultaneously in terms of soft-switching ability, galvanic isolation, and high-density power transmission. With regard to the control methods, numerous advanced controls are developed and proposed for the magnetic linked converter to ensure robust voltage control, smooth bidirectional power routing control, and high degree of decoupling to avoid any control interactions up to date. There have been a few review studies on the converter topology, control, and power management for magnetic-linked power converters for future for renewable energy integration to the traditional power grid, more electric aircraft applications, and electric vehicle charging implementation in the literature. However, a detailed review of magnetic-linked power converter topologies, controls, and power management on these applications is still limited in terms of a variety of power electronic interfaces with appropriate controls and power management. Therefore, this paper presents a comprehensive review with a more specific assessment of the variety of magnetic-linked power electronic interfaces with controls and power management for the widespread emerging applications.

INDEX TERMS Energy policy, electric vehicle charging applications, magnetic linked converter, power electronic interfaces, power management control strategy, renewable energy sources.

NOMENCLATURE

RESs	Renewable energy sources.
CVs	Conventional vehicles.
EVs	Electric vehicles.

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GI	Galvanic isolation.
PV	Solar photovoltaic.
PMCS	Power management control strategy.
PMCA	Power management control algorithm.
MLPC	Magnetic linked power converter.
DMLC	Dual-port magnetic linked converter.
MMLC	Multiport magnetic linked converter.
CS	Charging stations.
ESS	Energy storage systems.
MEA	More electric aircraft.
ZVS	Zero-voltage switching.
ZCS	Zero-current switching.
EMI	Low electromagnetic interference.
FPGA	Field programmable gate array.
GaN	Gallium-nitride.
HESS	A hybrid energy management strategy.
GA	Genetic algorithm.
TPC	Traditional power converter.
SPS	Single phase shift.
DPS	Dual phase shift.
EPS	Extended phase shift.
TPS	Triple phase shift.
PI	Proportional-integral.
DSP	Digital signal processor.
MPC	Model predictive control.
PMS	Power management strategy.
EMS	Energy management strategy.
DP	Dynamic programming.
PMP	Pontryagin minimum principle.
ECMS	Equivalent consumption minimization strategy.
SOC	State of charge.
SiC	Silicon carbide.
WT	Wind turbine.

I. INTRODUCTION

The total amount of carbon emissions worldwide is still increasing [1], [2], which is the main factor of climate change. This leads to global warming due to greenhouse gases tend to trap infrared radiation photons in a particular manner [3]. An alternative energy source to replace the traditional energy source, i.e., fossil fuels, has been pursued by the power industry. The renewable energy sources (RESs) become promising as a clean energy source to dwindle the demands from fossil fuels [4]. Since climate change becoming a pressing issue in the world, the emission of the greenhouse gas should be limited, and the RESs are proving to be a promising source of energy for the future. In this case, several countries have implemented policies aimed at reducing greenhouse gas emissions. Among these policies are commitments to decrease or halt the production of conventional vehicles (CVs) [5]. Renewable energy integration into the traditional power grid, more electric aircraft applications (MEA), and electric vehicle (EV) charging implementation will be the alternative and only available individual or public energy and transportation options in these countries. According to the up-to-date report in [5], renewable energy occupies 15.5% in the building sector, 16.8% of the industry sector 4.1% in the transport sector, and 15.5% in the agriculture sector, in which RESs are a small fraction of the total energy consumption in the transport sector in the year of 2022. Although renewable energy consumption remains at a low level, the report suggests the year 2022 has the fastest growth in the sector of transport and agriculture of adopting renewable energy. Renewable-based EVs and MEA have been replacing traditional systems which consume fossil fuels for the past several years. Therefore, to efficiently utilize renewable energy in the traditional power grid, MEA applications, and EV charging applications will ensure such a rate of green environment growth in the future.

The power electronics have been implemented to utilize renewable energy to the traditional power grid, MEA applications, and EV charging applications in multiple aspects. Although typical power electronics such as buck converters and boost converters can be used to charge an electric vehicle, their efficiency cannot be assured. Another major issue with buck/boost converters is insufficient energy management capabilities [2]. Because typical buck/boost converters, particularly for on-board charging stations, suffer from ineffective energy usage, for example, which is vital as energy generation from an electric vehicle's standpoint, researchers have looked at other options [6]. In addition, classic converters have various limitations, such as the typical rectifier bridge confronting high voltage stress and high circulation current in the freewheeling interval [6] and so on. The disadvantages of these converters still need to be addressed, which include limitations of input and output current and voltage range, lack of galvanic isolation, etc. Therefore, a new type of converter needs to be developed to complement the drawbacks of the aforementioned converters.

In recent years, magnetic-linked power converters (MLPC) have been gaining significant attraction in the power industry and have been applied to many emerging applications. The magnetic linked power converter was introduced in the 1980s which consists of a dual active bridge [2]. It was then widely adopted in the 1990s [2]. Comparing the magnetic linked converter with other DC-to-DC converters, it features such as the ability of high-power handling with less power loss during power conversion, galvanic isolation (GI) between the input and output circuitries, cost-efficiency of the components due to the relatively simpler design, and high efficiency with respect to power transmission have made it a popular candidate. In this case, the implementation of the magnetic linked converter can help to interface renewable energy integration to the traditional power grid, more electric aircraft applications, and electric vehicle charging implementation. The first magnetic-linked converter was introduced back in 1991 in the form of a dual active bridge configuration for various applications [2]. Since then, the magnetic linked converter has been developing with different topologies to suit various applications, such as an effective interface for renewable energy integration to the traditional power grid, more electric aircraft applications, electric vehicle charging implementation, etc.

Since last decade, researchers have given careful attention to utilizing different alternative renewable energy sources (RESs), for instance, wind, solar photovoltaic (PV), fuel cells, tidal, oceanic waves, and biogas [2] for developing vehicle charging station and other medium to high applications such as high voltage DC substation, medium voltage distribution line, etc. [1]. In addition to producing a significant reduction in CO_2 emissions, these alternative sources have many other advantages for vehicle charging stations such as their modular installation, high fuel efficiency, and less construction lead time compared to fossil fuel-based power plants [7]. Therefore, interfacing of MLPC for renewable energy integration to the traditional power grid, more electric aircraft applications, and electric vehicle charging implementation is considered the key solution for future individual or public transportation solutions to meet the fast-growing EV demand and ensure energy sustainability [8], as well as producing a significant reduction in CO_2 emissions [6] which is urgent for sustainable energy solutions.

A. KEY ASPECTS OF THE REVIEW

There is a need for sustainable energy solutions that can be connected to RESs systems to improve power quality and reliability. For sustainable energy solutions, magnetic-linked power converter technologies have been widely identified as a promising candidate for the utilization of renewable energy in versatile applications. Therefore, this review study aims to provide a detailed state of the art of magnetic linked power converter technologies for RESs tied to off-grid/on-grid systems for utilizing renewable energy. The purpose of this study is to provide a comprehensive and reliable review of the following aspects.

1) INVESTIGATION OF DIFFERENT TYPES OF ON-GRIDS/OFF-GRIDS MAGNETIC LINK CONVERTER TOPOLOGY FOR DIFFERENT VOLTAGE-LEVEL APPLICATIONS

It is very challenging to choose the best-suited topology in terms of design simplicity, simple control loop, less computational complexity, and cost-effectiveness, that can be realistically implemented for real-time applications that are connected to RESs. Therefore, a literature survey is needed to be conducted on various types of on-grids/off-grids magnetic link converter topologies to identify the best one for utilizing renewable energy for future green grid infrastructure.

2) INVESTIGATION OF DIFFERENT TYPES OF CONTROLLERS APPLIED ON MAGNETIC LINK CONVERTERS USED IN ON-GRIDS/OFF-GRIDS SYSTEMS

With the rapid advancement of advanced control technologies, magnetic link converters have proved to be highly reliable, efficient, controllable, fault-tolerant, and cost-effective solutions for the integration of RESs into numerous applications. With the overwhelming number of existing literature, a comparative investigation among the reported controllers needed to be carried out to identify the suitable one for each specific application.

3) INVESTIGATION OF DIFFERENT TYPES OF POWER MANAGEMENT STRATEGIES/ALGORITHMS/CONTROLLERS USED IN MAGNETIC LINK CONVERTER

To make the RESs integrated traditional power grid, more electric aircraft applications, and vehicle charging stations efficient, reliable, and cost-effective, a power management strategy/algorithm with advanced control decisions needs to be designed to control the energy flow among different direction. Therefore, an appropriate power management strategy/algorithm (PMCS/PMCA)/controllers need to be identified. In addition, the regulated voltage and frequency capability during ramping events of RESs are the basic requirements in modern grid applications. The PMCS/PMCA and its control should fulfill these jobs effectively. It is worth noting that the modern PMCS/PMCA with its control can successfully compensate for the voltage and frequency instability issues. Therefore, an investigation of different types of PMCA/PMCS is necessary.

This paper is composed as follows. A detailed literature survey on various types of on-grid/off-grid-integrated magnetic link converter topologies has been conducted in Section II. Section III presents different types of controllers. Different types of power management control strategies/algorithms (PMCS/PMCA) for utilizing renewable energy in low/medium/high voltage applications have been reviewed in Section IV. Section V presents discussions on further research that needs to be explored. Finally, Section VI brings this paper to a conclusion.

II. ADVANCEMENT IN MAGNETIC LINK CONVERTER TOPOLOGY FOR EMERGING APPLICATIONS

The magnetic linked power converter (MLPC) commonly can be categorized as two types, *i.e.*, dual-port magnetic linked converter (DMLC) and multiport magnetic linked converter (MMLC). They share the same operation principle, especially the modulation techniques. However, the DMLC is limited by its two-port topology. The power can only be transferred from one port to another port, which hinders the capability of high-density power transmission and the efficiency of the converter. On the contrary, MMLC possesses multiple ports and can be configured in various ways to facilitate bidirectional power transmission.

A. DUAL-PORT MAGNETIC LINKED CONVERTER (DMLC)

The design of the DMLC, which is shown in Fig. 1, was first presented in 1991. It showcases a high power density and the ability to convert DC power with high efficiency [2].

1) LOW VOLTAGE LEVEL APPLICATIONS OF DMLC

The DMLC is viewed as a vital component linking low-voltage applications, for example, electric vehicle charging stations (CS) and renewable energy networks. It has been

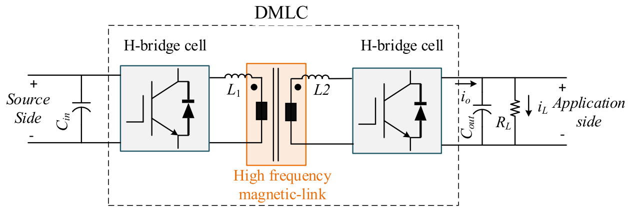


FIGURE 1. DMLC topology for interfacing between the source side and application side [2].

utilized either in off-grid or on-grid operation scenarios to serve as an interface among energy storage systems (ESS), renewable generation systems, and CS [9]. Fig. 2 shows the smart grid connected to the EV charging station through DMLC.

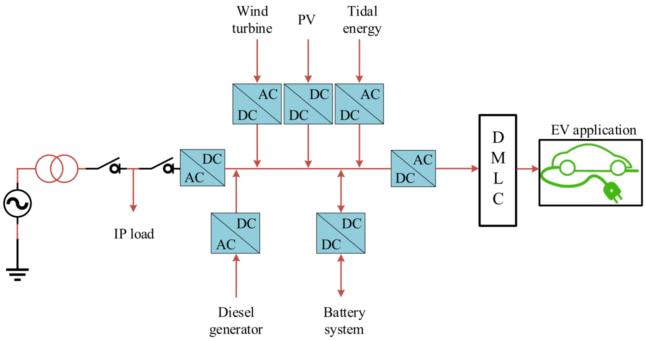


FIGURE 2. System topology for the smart grid connected to the EV charging station through DMLC [8].

The paper in [10] elaborates another application of the DMLC as an ESS for EV charging applications, and it includes an analysis of the issue of transformer saturation that arises due to DC-bias current. The study in [11] examines the robustness of the DMLC's galvanic isolation capability and concludes that the fault current will remain within the rated value limit under a specific modulation. The authors in [12] have explored the output impedance characteristic of the DMLC, while [13] has outlined a technique for modeling and simulating electromagnetic transients. The DMLC has been implemented in various applications, such as in more electric aircraft (MEA) [14], navel DC network [15] to supply instantaneous peak power to pulse power loads (PPLs), and in EV charging applications with both AC and DC networks utilizing cascaded rectifiers as shown in Fig. 3 and described in [16].

In [17], an analysis was conducted to evaluate the high efficiency and ability to handle large power ratings of the DMLC. The aforementioned literature, it is clear that the DMLC has several advantages including:

(i) High power density and high efficiency due to its compact size, high operating frequency, and the application of soft-switching techniques, such as zero-voltage switching (ZVS) and zero-current switching (ZCS).

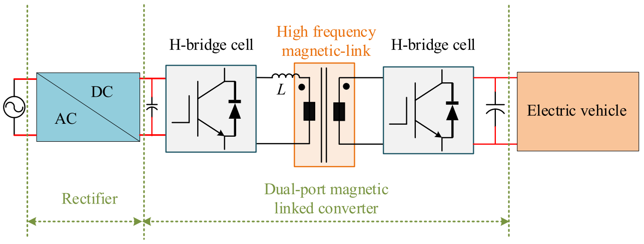


FIGURE 3. AC-to-DC EV charging application through DMLC [16].

(ii) Bidirectional power flow to enable DMLC can be the interface between the traditional power grid and the renewable energy system.

(iii) Low electromagnetic interference (EMI) provided by the high-frequency transformer to ensure galvanic isolation, as well as the reduced switching noise from the active bridge owing to the soft-switching techniques.

The literature [9], [10], [11], [12], [13], [14], [15], [16], [17] have discussed low-voltage applications of DMLC. However, the DMLC can be further used in medium and high-voltage applications as discussed in the following subsections.

2) MEDIUM AND HIGH VOLTAGE LEVEL APPLICATIONS OF DMLC

Normally, the DMLC is a single-phase device with the limitation of rated voltage level. In this scenario, as shown in Fig. 4, the author presents a modified structure of the DMLC that is suitable for applications with medium to high power requirements [18].

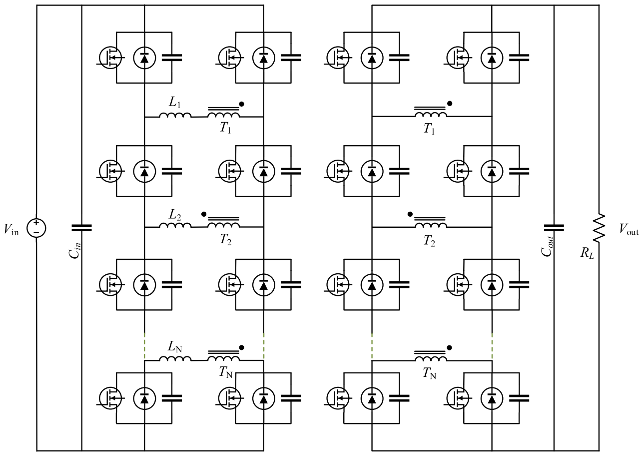


FIGURE 4. Series connection for dual-port magnetic linked converter for using medium to high power applications [18].

The medium voltage level has been achieved in this series connection of DMLCs. However, the issue of maintenance has not been resolved in the proposed design. If one of the individual DMLCs malfunctions, it becomes challenging to identify the specific point of failure. Furthermore, replacing a single DMLC demands the replacement of not only the active bridges but also the magnetic link, adding to the complexity and cost of maintenance.

Another proposed arrangement involves stacking several DMLCs in a series configuration to enable power to flow back and forth in directions. The DMLC modules are stacked together in high DC voltage applications to increase the fault-handling capacity, and this is facilitated by the modular design of the converter, as discussed in [19]. This modular design reduces the aforementioned complexity and expense of maintenance. However, the power conversion device still has a large size due to the presence of multiple magnetic links.

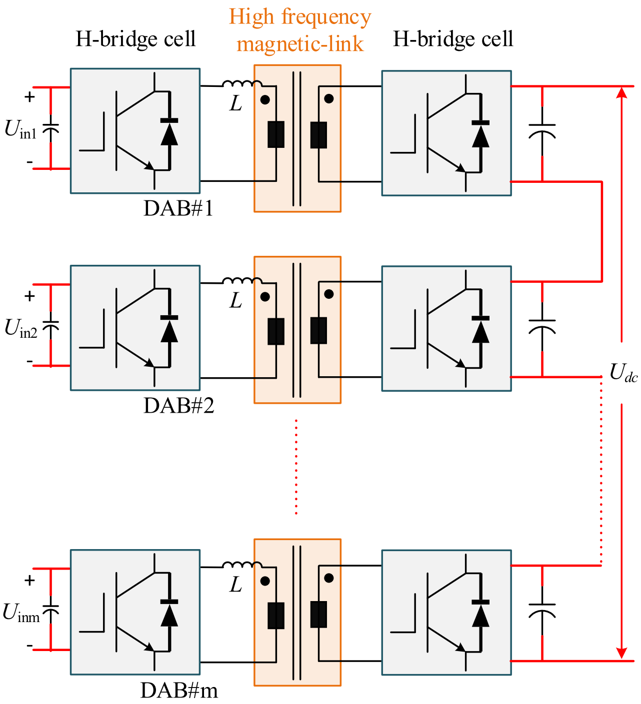


FIGURE 5. Configuration of DMLC for series connection for medium to high voltage application [20].

The DMLC configuration illustrated in [20] allows for separate or shared input voltage supply to the primary side, as illustrated in Fig. 5.

This configuration enables the hot-swapping of ESS and the ability to control the power-sharing ratio between each ESS. The proposed design also faces a similar issue related to the complexity and cost of maintenance. In the event of a single component failure at the output side, the entire output module will need to be replaced when these ports are connected in series. Moreover, the waste of the magnetic links should not be disregarded if the system requires a higher voltage, which would require more DMLCs.

Through the case study in [21], the author investigates the benefits of a modular configuration for the DMLC in high DC voltage transmission scenarios, demonstrating advantages in cost efficiency and maintenance stress reduction. Although the modular configuration resolves the maintenance issue, the device retains the bulky size with multiple magnetic links.

The issue of oversized and power loss is addressed through a superposition configuration of the DMLC as proposed in [22]. This involves combining the primary and secondary bridges to eliminate these problems. The configuration presented in [22] is shown in Fig. 6.

The utilization of an auxiliary-resonant commutated pole in a three-phase DMLC configuration is proposed in [23] to decrease switching loss. The technique employs a field programmable gate array (FPGA) to rapidly detect zero-voltage crossing, allowing for fast switching operation.

In terms of switching loss, the subsequent section will discuss how the performance of the DMLC is affected by the switches' material.

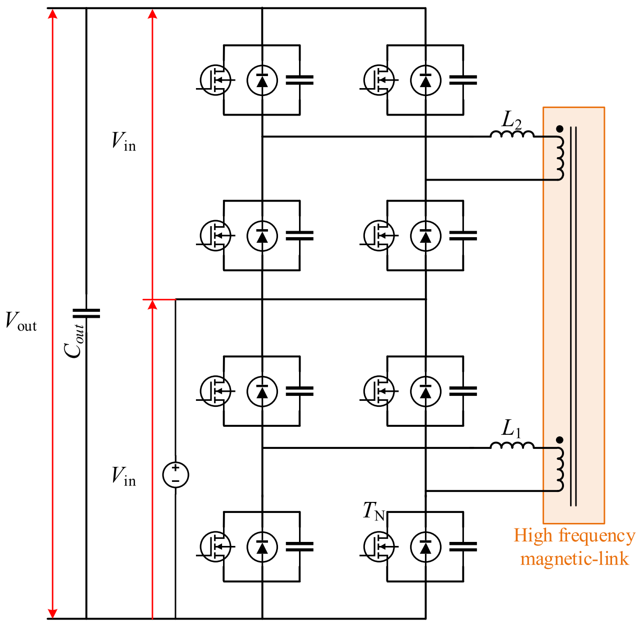


FIGURE 6. Superposition of dual-port magnetic linked converter for medium to high voltage application [22].

3) DIFFERENT TYPES OF SWITCHES USED IN THE ACTIVE BRIDGE OF DMLC

Switch performance in constructing active bridges of DMLC varies depending on the material used, particularly the power loss on the switches. In selecting the appropriate semiconductor, it is important to consider those with low blocking voltage and small intrinsic resistance, to achieve low switching loss even under ZVS operation. A novel DMLC has been introduced in [24], which employs transistors with high electron mobility using gallium-nitride (GaN) to overcome the power loss issue in light load conditions, thereby achieving an efficiency of 98.3%. In [25], a comparison is made to evaluate the performance of different types of switches used in the DMLC. One approach uses silicon carbide (SiC) material for SiC-MOSFET switches to reduce power loss as presented in [26]. Moreover, the author compares the performance of SiC-MOSFET and IGBT switches. In [27], semiconductor selection analysis is conducted, and the paper discusses the selection of capacitors and heat sink systems for the converter circuit. Therefore, the use of novel materials, such as GaN and SiC, results in a higher performance. The switching loss can be significantly reduced on the active bridge.

In summary, it is evident that the DMLC possesses the versatility to manage various voltage levels, whether in low-voltage applications or medium- and high-voltage level implementations, through the use of different topologies and the incorporation of additional components. However, the drawback of using DMLC is obvious. The output voltage is limited to the output terminal of a single DMLC. In a medium- or high-voltage application, the configuration of the DMLC needs to be adjusted by either stacking up multiple DMLCs or connecting them in series and parallel configurations, as described earlier. This results in another issue, which is that if one of the DMLCs malfunctions during operation, this entire DMLC must be replaced. Additionally, if the device only utilizes DMLC as a power transmission component, it will increase the number of magnetic links, leading to an increase in device cost and maintenance expenses, as well as the loss of compactness.

To address the aforementioned issues in DMLC, the MMLC configuration can be implemented where each port of the MMLC can share the same magnetic link. This results in the maintenance only requiring changing the active bridge on each port. Moreover, if the magnetic link fails, the cost can still be limited as there is only one core in the entire device. Therefore, compared to the DMLC, the MMLC topology reduces the cost of maintenance and simplifies the process of repairing the system.

The efficiency of the active bridges on the DMLC in improving device performance was discussed earlier, and it is emphasized that the material used for the switches is crucial in achieving this. It is particularly relevant because both DMLC and MMLC employ active bridges, hereby the benefits of using advanced switch materials can be shared between them.

B. MULTIPORT MAGNETIC LINKED CONVERTER (MMLC)

As the active bridges of the MMLC share the common magnetic link while it is operating in the same manner as the DMLC, the limitation and disadvantage of the topology of DMLC discussed earlier can be overcome by using MMLC, which has the ability to reduce the size of the device without compromising performance. The MMLC configuration can be customized to have either one power supply port with multiple output ports, or multiple power supply ports with one output port, or multiple power supply ports with multiport output ports. All the ports share the same magnetic link for power transmission. Additionally, the MMLC is capable of high-power density transmission, which is suitable for the application of transportation and motor traction. The ability to convert high- and medium-voltage into low-voltage, which can be independently used for interfacing renewable energy systems with traditional distribution networks. The merit of efficiency allows the MMLC to be implemented in the solid-state transformer.

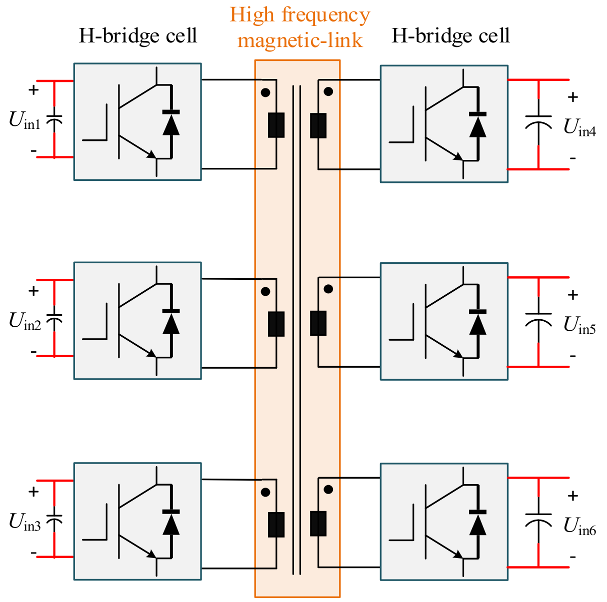


FIGURE 7. Topology of multiport magnetic linked converter with six ports in more electric aircraft application [28].

The MMLC has been increasingly utilized in various applications such as MEA as shown in Fig. 7, due to its lightweight and cost-effective features, as reported in [28]. The MMLC structure proposed in [28] comprises six active bridges distributed symmetrically on both sides of the magnetic link. This design allows for the distribution of power to loads using either two or three power supply sources. The power supply and loads share the same magnetic link reduces the device size. The design of the MMLC involves the separation of active bridges on either side of the magnetic link, which allows for greater flexibility in power balance. The active bridge on the load side of the MMLC can either be connected to individual loads or combined to supply a single load that requires more power. This design also guarantees a redundancy feature where if one of the active bridges fails, the other active bridges can continue to supply power to the load.

The impedance model of the MMLC has been reported in [29] for interfacing the electrical distribution network in MEA applications. The paper utilizes a quad-port magnetic linked converter, which has four active bridges, to establish an impedance model for the system's input. The results demonstrate that the operating conditions can be extended to a broad range by predicting the impedance model from the input side of any type of magnetic-linked converter. This further validates the versatility of the MMLC for applications related to transportation.

Another advantage of the MMLC lies in its ability to interface multiple power sources and loads with multiple input and output ports, which leads to the application of integration for traditional power grid and renewable generation system. Detailed specifications for the integration of solar panels and ESSs with the grid have been investigated in [30], while [31] demonstrated the wind turbine (WT) application of MMLC for medium voltage networks in renewable energy integration.

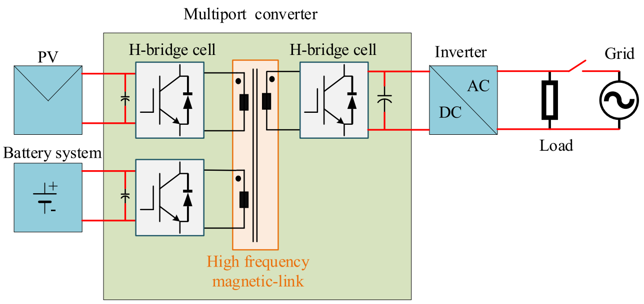


FIGURE 8. Integration of AC power grid and solar generation system via multiport magnetic linked converter [30].

The integration of AC power sources and solar generation systems can be achieved by adding additional power electronic devices, such as rectifiers and inverters, to the MMLC as shown in Fig. 8. This arrangement permits the power supply and ESS to be linked to the DC bus through the MMLC and facilitates the integration of traditional power supply via other power electronic devices. In this manner, the loads can be supplied power from all the power sources in the system. While more research is needed in the areas of control strategies and modulation methods, the MMLC is considered to be a crucial component for the future smart EV charging station.

The authors in [31] mentioned the use of a three-phase MMLC to link a wind turbine (WT) system with the traditional power grid in varying wind speed conditions as shown in Fig. 9. The proposed MMLC offers individual control of each port, enabling power management and bi-directional power flow. In this work, the proposed topology of the MMLC has reduced the device size and demonstrated its advantages in terms of reliability and efficiency.

In [32], a source energy router with reconfigurable features was proposed using MMLC as depicted in Fig. 10. The efficiency of the MMLC has been improved by the author through the connection of twelve active bridges to a single magnetic link. The modular design of the active bridges allows for quick maintenance service. The proposed topology functions as a transformer to step down high voltage into low voltage and manage power flow in a sophisticated manner, which is to adjust the phase angle of each input voltage to induce different currents on the primary side windings.

The MMLC has also been used for traction purposes in [33]. The proposed configuration employs the MMLC as the interface which connects rectifiers and inverters on each side as illustrated in Fig. 11. In this system, the rectifiers are connected in series on the power supply side to obtain power from the AC medium-voltage source, and then transfer DC power to the MMLC. A group of inverters connected to the output side of the MMLC drives the traction motors. In this setup, the MMLC is utilized to transfer power from the medium-voltage power source to the low-voltage rated load, which is the traction motors. This exemplifies the advantage of the topology of MMLC, which makes the MMLC a better device than the DMLC.

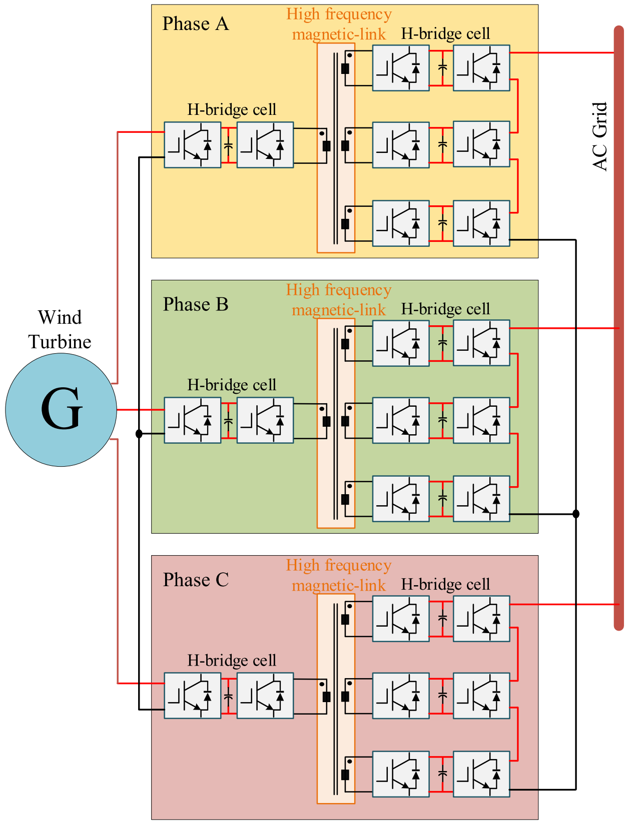


FIGURE 9. Multi-level multiport magnetic linked converter in wind turbine generation system connected to the traditional grid [31].

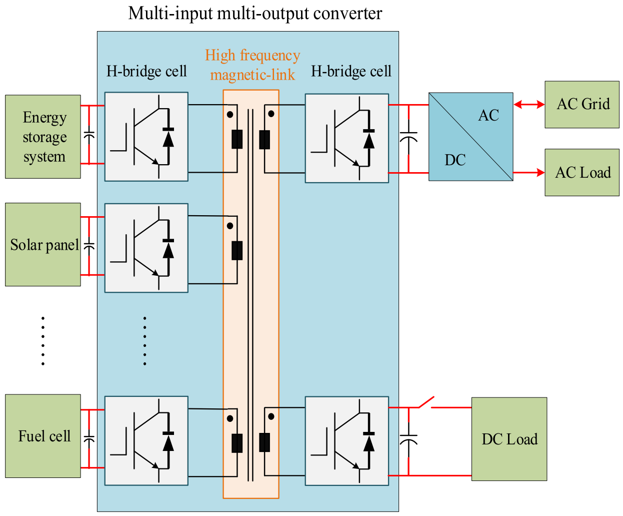


FIGURE 10. Energy router application with multiport magnetic linked converter [32].

Similarly, the traction application of the MMLC is used for electric vehicles described in [34] as shown in Fig. 12. The MMLC has demonstrated its capability in providing high-density power transmission in this application. More

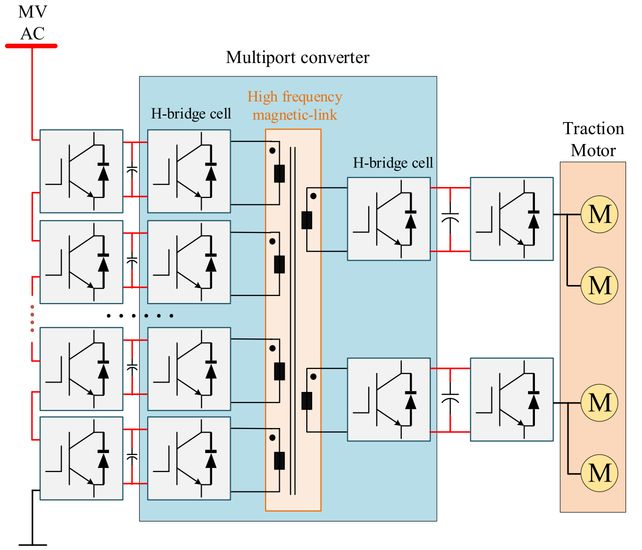


FIGURE 11. **The multiport magnetic linked converter used in electric train traction system [33].**

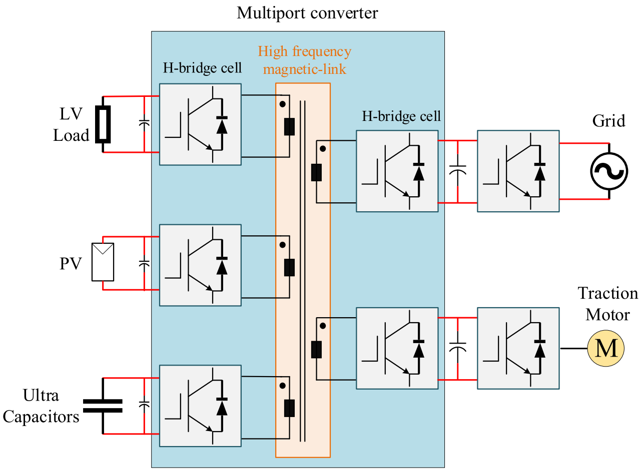


FIGURE 12. **Multiport magnetic linked converter used to connect renewables for traction application [34].**

specifically, it has efficiently supplied the motor with sufficient torque to meet the diverse force requirements. The power supply in this scenario comes from two sources, which are the main power grid and a renewable energy source. The MMLC functions as an energy router that collects energy from both sources and distributes it to various loads, such as the traction motor, other onboard loads, and the battery charging system.

Furthermore, the MMLC has been applied as a power solid-state transformer (SST) as shown in Fig. 13. The SST application is another important application for the MMLC. Compared to conventional transformers as reported in [35], [36], and [37], the MMLC implementation improves efficiency in power transmission and significantly reduces the size of the device. Additionally, the SST utilizing the MMLC can respond rapidly to changes in different load conditions, especially in the power distribution network.

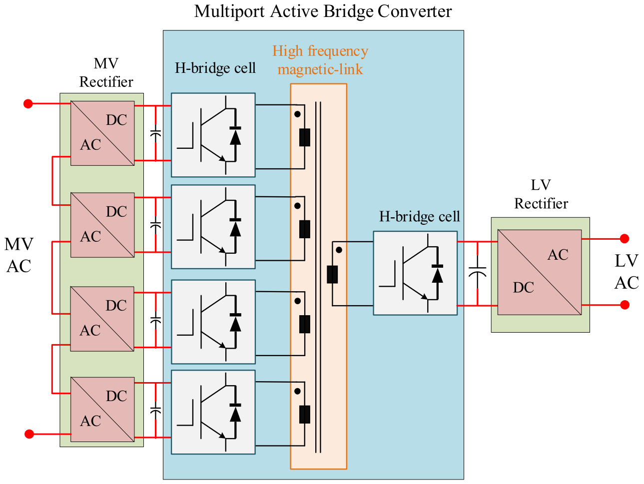


FIGURE 13. **Solid-state transformer using multiport magnetic linked converter for different voltage level applications [37].**

Regardless of the number of active bridges connected to the magnetic link, the MMLC has the same capability as the DMLC in terms of providing galvanic isolation. A study regarding fault analysis has been conducted, revealing that the MMLC ensures the reliability of smart transformers [38]. Typically, in the event of a fault, the options for resolving the issue are either replacing the faulty component or implementing a redundant design. However, the proposed solution for maintaining power flow within the system involves the use of MMLC to redirect power flow through the remaining functional active bridges. This is achieved by utilizing sensors to detect the fault location and reconfiguring the circuit through an algorithm, which ensures cost-efficiency. The investigation of topology, modulation method, control technique, and fault tolerance for the MMLC has been conducted in [39]. The author presented a new topology for the MMLC aimed at improving the fault-handling capabilities of high-power DC distribution systems. This innovative topology includes the addition of two extra switches that connect to the upper switches of the conventional full active bridges of each port. These additional switches enable bi-directional power flow control and allow the system to continue operating even in the presence of faults. In this case, by making slight modifications to the topology of the MMLC, it has been demonstrated that the capability and versatility of the MMLC are further enhanced. This serves as additional evidence that the MMLC represents an optimal topology for magnetic-linked converters.

Overall, it can be seen that the MMLC has equal capabilities that the DMLC has while reducing the device size and costing less in maintenance expenses. Furthermore, the MMLC shares the same modulation strategies and control approaches as the DMLC. These two aspects are also important in operating the magnetic-linked converter in general. In the next two sections, the control techniques will be addressed following the discussion of modulation strategies, as the choice of control methods depends upon the specific modulation strategy that is employed.

III. CONTROLLER FOR MAGNETIC LINK CONVERTER FOR EMERGING APPLICATIONS

A. MODULATION METHOD FOR THE MAGNETIC LINKED CONVERTERS

There have been several modulation methods used in MLPCs. The phase shift modulation is one of them which is derived based on the theory of voltage angle difference to control power flow through any two ports of the MLPC. Fig. 1 has already illustrated the basic DMLC topology of the magnetic linked converter. The phase shift modulation will be discussed based on that topology. The most commonly used phase shift modulation methods are single phase shift (SPS), dual phase shift (DPS), extended phase shift (EPS), and triple phase shift (TPS).

The SPS method has been implemented in [39] and [40] for analyzing the performance of the MMLC and controlling dynamic power. A novel MMLC proposed in [41] adopted SPS modulation for improving the reliability of a solar generation system.

Under the SPS modulation method as depicted in Fig. 14, the duty ratio for each switch on every active bridge is configured to 50%. Following that, the four switches on the primary side of the magnetic link are divided into two sets, which are S_1S_3 and S_2S_4, functioning in a complementary manner during the operation cycle T_s. This implies that when one set of switches is turned on, the other set will be turned off. Likewise, on the secondary side, two sets of switches S_5S_7 and S_6S_8 operate in the same way but not simultaneously with the primary side.

In the SPS, D determines the timing for turning on or off the secondary switches. By employing this SPS, the input power charges the leakage inductor of the magnetic link. When the secondary switches are turned on, the power stored in the leakage inductor is transferred to the output side of the magnetic link.

The merits of the SPS modulation can be summarized as below [42]:

1. The simplicity of the SPS modulation reduces the computational burden for the controller. As there is only one phase shift variable to control, the implementation is relatively easier than other modulation methods.
2. The switches on the active bridges can achieve ZVS easily. The dead ban of switches can be utilized for such purposes. When the first set of switches is fully off, the subsequent set of switches can be turned on. This ensures no voltage across the active bridges during the switching period.
3. The ZVS contributes fewer power losses to the magnetic-linked converter, which leads to less voltage stress on the switching stages. This further improves the reliability and stability of the system.

However, the SPS modulation has its limitations. Since current stress will increase considerably if the power conversion ratio is not equal to 1 using SPS modulation, the authors in [43] analyzed DPS under specific transmission power and power conversion ratio.

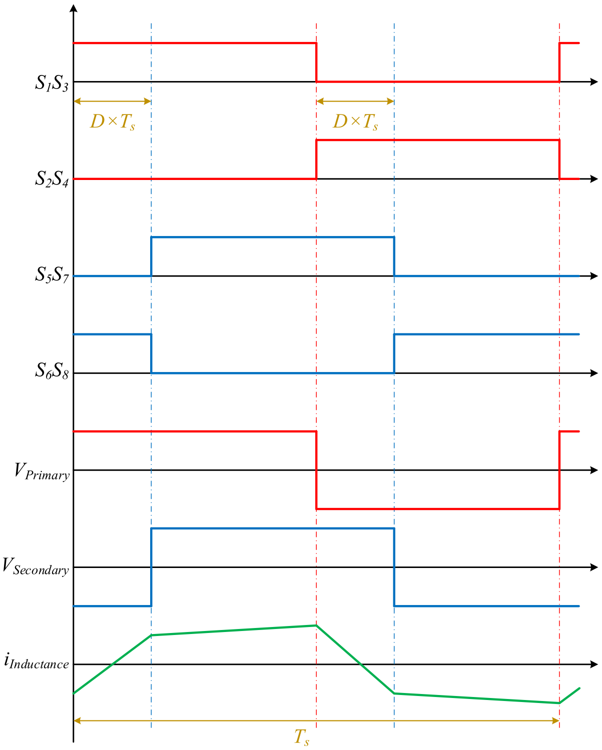
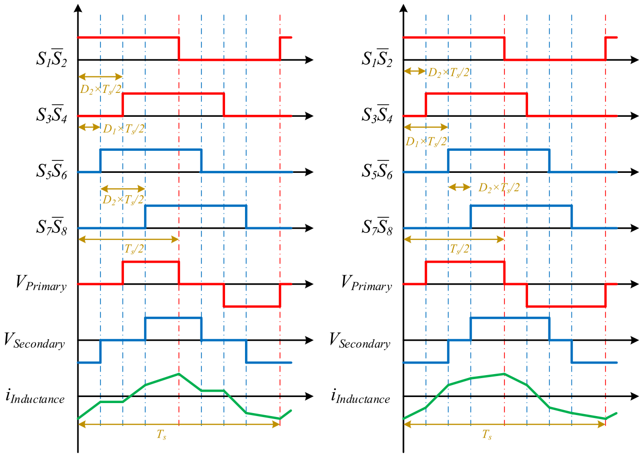


FIGURE 14. **Single phase shift modulation for magnetic-linked converter [42].**



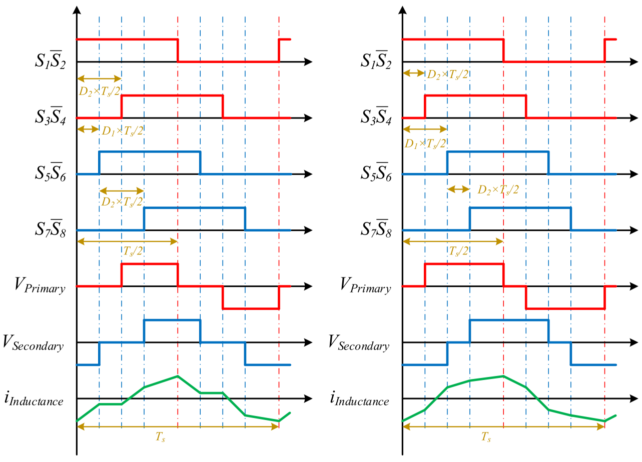
(a) (b)

FIGURE 15. **Dual-phase shift modulation for magnetic-linked converter. (a) $D_1 < D_2$. (b) $D_1 > D_2$ [43].**

The DPS modulation involves two phase shift values, D_1 and D_2. According to [43], an additional phase shift value D_2 is introduced between the switch sets that belong to the same active bridge as shown in Fig. 15. However, the phase shift D_1 that is between the input and output active bridges remains unchanged, as previously explained in the context of

SPS modulation. This improves the control flexibility when operating the magnetic-linked converter. Additionally, the DPS modulation enhances the power transfer capability and effectively addresses the circulating current issue encountered in the SPS modulation.

The DPS modulation was proposed in [44], [45], [46], and [47] to enhance system efficiency and decrease inrush peak current, leading to high efficiency of power transmission. Comparing SPS and DPS indicates that DPS can reduce switch stress under the same power transfer capacity [48], which has been verified in [49] as well. Another study comparing the SPS and DPS modulation methods examined the effect of equivalent series resistance of power induction and introduced the use of asymmetric double-side modulation for the DMLC [50]. While the DPS modulation offers improved performance, it is important to acknowledge that it also introduces increased complexity and higher power losses during switching transitions when overlapping occurs, in comparison with the SPS modulation. A novel triangular DPS modulation method has been implemented in MMLC for analyzing both balanced and unbalanced load conditions [36]. The modulation technique used in this application is based on the DPS modulation method with modifications to the input and output voltage levels, which lead to variations in the induced current on the magnetic link. The aforementioned modulation method has a drawback in the form of a large amount of reactive power circulating in the high-frequency transformer when the operating angle of phase-shift is large.



(a)

(b)

FIGURE 16. Extended phase shift modulation for magnetic linked converter. (a) D_{E2} is on the primary side. (b) D_{E2} is on the secondary side [51].

In [51], EPS modulation method was also evaluated through simulation together with SPS and DPS [51]. The outcome of the simulation showed that the SPS modulation method caused the highest level of switch stress, while the DPS and EPS methods caused the least amount of stress.

As shown in Fig. 16, the EPS modulation shares similarities with the DPS modulation in terms of utilizing two phase shift values, namely D_{E1} and D_{E2}. D_{E1} is responsible for controlling the phase difference between the active bridges on the input and output sides, while D_{E2} is applied to a single side of the active bridge, either on the input or output side. Since the EPS modulation is derived from the DPS modulation, it inherits both the benefits and drawbacks associated with DPS modulation.

On the other hand, the TPS modulation method is designed to tackle the issue of transient bias current on the DC bus, which causes transformer saturation [52], [53]. Additionally, TPS enables the magnetic-linked converter to perform ZVS, as described in [54] and [55], which can reduce power loss and improve efficiency during low-load condition operation [56]. Moreover, TPS can also help to minimize switch stress for the magnetic-linked converter in [57]. Furthermore, a hybrid modulation method, which combines conventional phase shift modulation and triangular current modulation, is discussed in [58] with a detailed comparison.

TPS modulation serves as an alternative modulation technique for regulating the magnetic-linked converter. In this modulation, three-phase shift values, namely D_{T1}, D_{T2}, and D_{T3}, are utilized. As depicted in Fig. 17, each switch set is assigned a specific phase shift value relative to the reference switch set. This modulation method further enhances the capability of controlling power flow within the magnetic-linked converter, surpassing the DPS and EPS modulation techniques. Nevertheless, the utilization of three phase shift values in the modulation introduces noticeable additional complexity, making the implementation of TPS more challenging. The derived algorithm places a heavy computational burden on the microcontroller, leading to an unnecessary increase in power consumption.

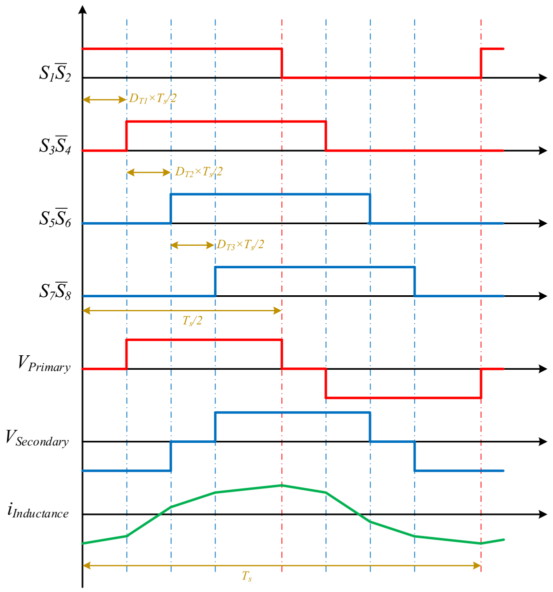


FIGURE 17. Triple phase shift modulation for magnetic-linked converter [52].

Since the DMLC is the basic element of MMLC, they share the same modulation method and control approach. Due to the simplicity of operating the MMLC under the SPS modulation, the SPS modulation method is considered as it requires only one variable to manipulate, which demands a relatively slower control device than other controllers. On the other hand, one control variable results in less computational burden. This also increases the response time from the controller.

B. CONTROL APPROACHES FOR THE MAGNETIC LINKED CONVERTERS

Generally, the closed-loop control method for both the DMLC and MMLC can be classified into two main categories, namely, linear control technique and non-linear control technique.

The conventional approach for linear control is the proportional-integral (PI) control method. To address the problem of voltage dips at the output of the DMLC, which is connected to the energy storage system, the virtual DC machine control method with PI control was employed [58]. Similarly, a PI controller suggested in [59] and [60] provides two phase shift variables virtual inertia control to the converter to regulate the power flow as shown in Fig. 18. Despite the improvement in control performance of the magnetic linked converter achieved by the PI controllers proposed in these references, the issue of overshot on the output waveform during the transition point cannot be neglected.

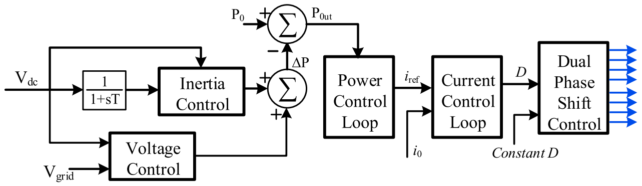


FIGURE 18. Diagram of DMLC with virtual inertia control strategy [60].

The response time is an essential parameter indicating the performance of the controller. However, the linear control method manifests slow response time in general. The slow response time of the PI controller has led to the development of the direct power control method that builds upon the PI control method [61]. To enhance the transient response time of the DMLC, a feedforward control technique operating with the PI controller has been proposed in [62] to control the inductor's peak current as shown in Fig. 19.

Another study focused on improving the transient response of the current in the DMLC by combining feedforward peak-current-mode control and predictive current control [63]. Although the proposed method reduces the demand for hardware, i.e., dedicated current sensors, the additional loop for the PI controller places extra complexity on the control algorithm. By employing the aforementioned techniques, the response time has been enhanced compared to traditional PI controllers. However, there is still room for further improvement in the response time.

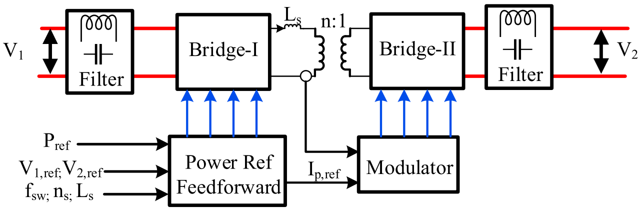


FIGURE 19. Peak current mode control of DMLC achieved based on power reference feedforward [62].

The author proposed an algorithm utilizing the PI control technique to address the issue of voltage variation in ESS and expand the soft switching region [64]. In [64], the author has proposed a method to control each switch in the DMLC individually by modifying the duty ratio. It eliminates DC offset in inductor current and transformer magnetizing current during transient states with a settling time that is less than half of the switching period. However, the issue of overshot can still be observed during load transitions.

To enhance the dynamic performance and the ability to handle disturbance, a phase shift controller has been proposed, which uses a model-based control method [65], [66]. This extends the previous work reported in reference [67]. Although the experimental results have shown that the model-based phase-shift control is effective in reducing reactive power in the magnetic link and suppressing output voltage ripples, the voltage sag exists on the output waveform. The article [68] describes a virtual direct power control method as shown in Fig. 20 that has been successful in achieving a fast dynamic response without overshooting at the output, but the complexity increases significantly in the implementation.

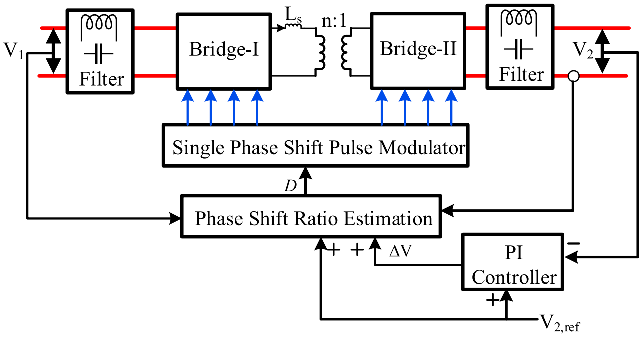


FIGURE 20. Virtual direct power control of DMLC [68].

While the linear multi-loop control method proposed in [69] reduces the voltage sensitivity to load changes, its implementation becomes more complex due to the need for multiple control loops.

To conclude the linear control methods, these have limitations in handling dynamic change in the system. Disturbances can significantly affect the system's response. In this case, linear controllers have their drawbacks in achieving the desired performance in order to operate magnetic-linked converters effectively. Moreover, linear controllers cannot rapidly stabilize the system due to their intrinsic sensitivity, which leads to overshooting and undershooting at the output.

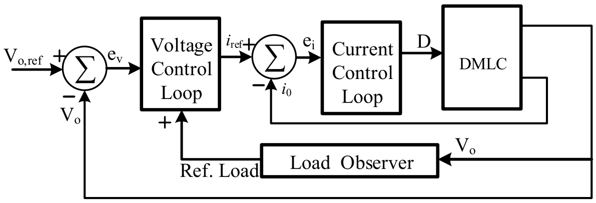


FIGURE 21. **Block diagram of dual loop sliding mode control of DMLC [71].**

To address the demerits of the linear control methods, non-linear control techniques have been proposed to attain robustness and quick dynamic response. The outer voltage control loop of the controller has been improved in terms of bandwidth by utilizing the predictive current mode controller as suggested in [70]. Nevertheless, the PI control method was still used in combination and a piece of extra equipment was added on for compensation. In [71], the sliding mode control method was evaluated and compared with the traditional PI control method.

The control structure is shown in Fig. 21. The Outer loop is a voltage loop, in which the voltage is the controlled object and e_V is the input. Moreover, the inner loop is a current loop, the output of the voltage controller is the input of the current loop controller, and the current loop controller tracks the output current reference signal i_0. The inner loop is a current-fed loop to improve the dynamic response.

While the sliding mode controller was found to handle transient load changes better than the PI controller, the output voltage comparison revealed the presence of a significant voltage sag. However, the findings presented in these references indicate that non-linear control approaches exhibit superior transient performance and reduced overshoot and undershoot compared to linear control methods. In [72], a compensation method is presented that estimates system disturbances using an observer. The observer monitors the system and estimates the disturbance when it is added to the input of the system. The output from the system is compared with the reference output, and the estimated disturbance is computed using an ideal model of the system. The compensation is then made by designing a filter for the input signal. A different controller that utilizes a reduced-order observer is described in [73] as an approach to managing power flow and decreasing circulating current in the DMLC.

Another type of control method for the MMLC lies in the neural network-based control technique. In [74], the author proposes a machine-learning method for accurately controlling the MMLC with six ports. The system employs one microcontroller and another digital signal processor (DSP). The system structure of the proposed control scheme is shown in Fig. 22. It shows the fast response to the output power. However, the training process is time-consuming. Furthermore, parameter changing will result in new training sessions for the DSP, which burdens the computational stress.

Several advanced control schemes for controlling power electronic converters, such as the hybrid fuzzy logic sliding mode controller (HSMC) [75], Laguerre function-based model predictive control (MPC) [76], PID-PSO robust control algorithm [77], and an optimal dead-time control scheme with burst-mode operation [78], have been proposed, designed, and presented. An improved dead-time for the PSFB converter has been presented and experimentally proven in [76], allowing for natural burst-mode operation. As a result, great thermal performance and low power consumption are possible at both heavy and light loads. Designing the A/D (analog to digital) converter using a field-programmable gate array (FPGA)-IC reduces the controller's size while increasing flexibility. The hybrid fuzzy logic sliding mode controller may improve the dynamic characteristics, stability, and resilience against disturbance; and can readily alleviate the chattering demerits, output current, and voltage ripples of the PSFBC by altering the SMC gain [75]. The Laguerre function-based model predictive control (MPC) scheme is a great choice for PSFBC because it has numerous significant benefits over traditional PI-based controllers, including non-linear peak input current limitations and various physical constraints [78]. Furthermore, the proposed controller in [78] has been experimentally tested and confirmed. The Laguerre function-based model predictive control (MPC) method is an effective control technique for the isolated phase-shifted full-bridge converter. Fig. 23 shows a simple block diagram of an MPC controller. This method generates an optimal control sequence that improves performance and efficiency. The MPC algorithm is capable of forecasting the phase shift value by employing the MMLC model based on SPS modulation, empowering it to make intelligent judgments regarding how to supply the system to attain the desired output.

An improved backstepping control scheme for a n-dimensional strict-feedback uncertain nonlinear system as like MMLC based on command filtered backstepping and adaptive neural network backstepping has been presented in [79] where convex optimization and soft computing technique are adopted to design the update law of the weights of the neural network, and Lyapunov stability criterion is used to prove the stability of the closed-loop system. The advantage of the proposed approach is to show it is highly effective with having a system of non-linear multi stage components like DMLC and MMLC. The problem in the proposed controller is that the high-order time derivatives of virtual control functions can result in explosive complexity in the controller design.

Ge and Wang in [80] developed an adaptive NN control scheme for a general class of nonlinear systems. Such a control scheme solved in both standard backstepping and command-filtered backstepping. Results found that adaptive NN backstepping is capable of dealing with nonlinear systems with completely (or partially) unknown and complex uncertainties, and without calculating the high-order time derivative of virtual control functions.

Zheng et al. in [81] developed a practical finite-time command filtered backstepping control method for a class of uncertain nonlinear systems with unknown control direction coefficients, unmodeled dynamics, and external disturbances. In order to address the design difficulties caused by the system unknown control direction coefficients, a virtual control direction method is presented by using a system equivalence transformation. This method is applied to a direct current motor control of a nonlinear system, and experimental results demonstrate the effectiveness of the proposed control scheme.

The literature mentioned above highlights the benefits of non-linear control methods over linear ones, showing greater robustness in the system output and addressing issues of overshoot and undershooting.

IV. POWER MANAGEMENT STRATEGY/ALGORITHM (PMS/PMA)/CONTROLLER FOR THE MAGNETIC LINKED CONVERTERS

A. POWER MANAGEMENT

Power management strategies (PMSs), also known as energy management strategies (EMSs), have been studied for tens of years, and several solutions have been improved. Existing PMSs can be divided into rule-based ones (such as rule-based strategies [82] and fuzzy logic-based methods [83]), global optimization-based PSMSs by employing algorithms like dynamic programming (DP) [84] and Pontryagin minimum principle (PMP) [85], instantaneous optimization-based PMSs (such as equivalent consumption minimization strategy (ECMS) [86] and MPC [87]), as well as machine learning and deep learning based PMSs (like Q-learning [88] and deep Q-learning [89]).

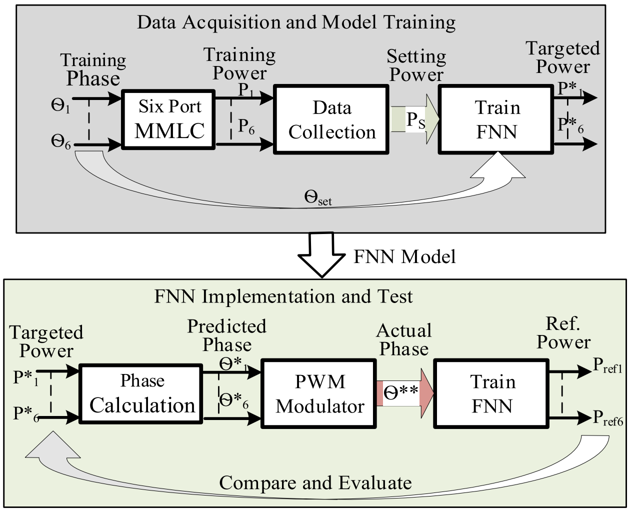


FIGURE 22. **Block diagram of machine learning control architecture of the MMLC comprising a 6-port MMLC [71].**

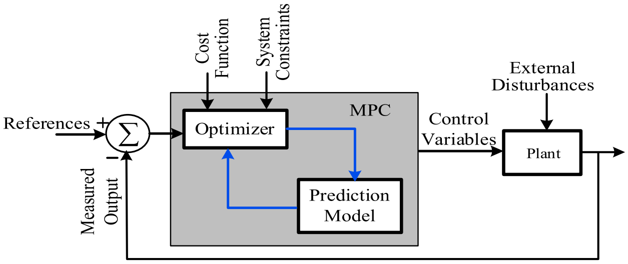


FIGURE 23. **Simplified block diagram of an MPC-based controller.**

The amount of current induced in the magnetic winding is determined by the phase shift value between the active bridges, as discussed earlier in the modulation methods. This governs power transmission from the input to the output, as well as enabling control over the power level on each port of the MMLC according to the desired specifications. Furthermore, by controlling the phase shift angle, the power transmission can be reversed from what was the output port to the port that previously supplied power.

To facilitate power flow within the MMLC, a combination of transient current control and an analytical approach for controlling power flow is proposed in [39]. The algorithm introduced in this paper effectively manages the transient current on each port. By employing a high switching frequency, this approach successfully transfers power between any individual port and two other ports with distinct power ratings. The regulation of power flow by controlling the induced current is presented in [73]. Despite the bi-directional power flow being accomplished, 78% inrush current can be observed on the output waveform. Furthermore, the extra loop for the current control enlarges the computational burden for the microcontroller. In [90], a simple approach for calculating the voltage phasors of each port for the MMLC is discussed, which can solve the power management issue of the MMLC with n-ports. It shows good results for the output waveforms of both voltage and current. However, the proposed approximation model has its errors which cannot be ignored.

To summarize, while the power management methods discussed in various references may differ, their ultimate objective remains the same. It is crucial to achieve bi-directional power flow in the magnetic linked converter, particularly in the case of the MMLC, which offers versatility in power transmission between multiple ports. This introduces the need for individual power control for each port, as different types of loads may have varying power requirements based on their specifications. Therefore, each port must be carefully controlled to provide the appropriate power accordingly. This requirement brings challenges to the inherent characteristic of the MMLC, namely, its cross-coupling nature.

From the vast PMS/PMA/controller available, Table 1 provides an overview of some recent research findings on-various types of PMS/PMA/control strategies and topologies of magnetic-linked converters.

TABLE 1. An overview of some recent research findings on different types of PMCS/PMCA, Control strategies and topologies for RESs integrated magnetic link converters.

Authors, Publication Year, and Reference	Proposed energy/power management strategy or control methods	How/what technique is used?	Topology used/proposed in the research	Applied fields/Research outcomes
Allegra et al.., 2013, [91]	A bang-bang management strategy/ Inversion-based control scheme	SOC-based supervisory method	Two-chopper configuration	Fulfillment of demand by sharing energy between energy storage devices
Travao et al., 2013, [92]	A two-level scheme for energy and power management/ Integrated rule-based meta-heuristic control approach	Framed rules for power split strategy	Dual-source electric vehicle topology	A first-level or long-term management related to energy strategy uses RBC. A second level or short-term management related to power strategy uses a meta-heuristic technique.
Hredzak et al., 2014, [93]	A MPC for energy storage system	SOC-based energy buffer system	hybrid battery-ultracapacitor power topology	Maintain the battery current, battery SOC, UC current, and voltage within the fixed limits.
Ferreira *et al*., 2008, [94]	A fuzzy logic supervisory control strategy	Cascade control, equivalent consumption minimization strategy	Multiple-input power electronic converter topology	Highly efficient operation of each power source to regulate the peak voltages and currents as well as the average power demand
N. Mohamed et. al., 2021, [95]	A straightforward power management algorithm/ Balance of forces acting control scheme	First stage supervisory approach	Wireless charging station consisting PV, fuel cell (FC), and a battery	Contribution of more than one energy source for charging a vehicle, even if the car is in motion status
Y. Zhang, et. al., 2023, [96]	A Cooperative power management algorithm/ Adaptive neuro-fuzzy inference control scheme	Advanced internet of vehicles framework in power management	Operation zone based range extended EV charging topology	Self-learning explicit equivalent minimization consumption application
A. Mehraban, et. al., 2023, [97]	An integrated optimal energy management strategy/ Constrained Pontryagin's minimum principle strategy	A cost-effective sizing algorithm	Flywheel energy storage in a battery electric vehicle topology	Extension of the battery cycle life and drive range by relegating fast dynamics of the power demand
M. Li, et. al., 2021, [98]	An adaptive real-time energy management strategy/ Random forests (RF) control method implemented by support vector machine	A multi-objective grey wolf optimizer	Powertrain configuration composed of, UC, dc/dc converter, and transmission system.	Sizing optimization and energy management strategy in electric vehicles
L. Zhang, et. al., 2018, [99]	A hybrid energy management strategy (HESS)/ Fuzzy logic, frequency decoupling, and state machine control strategies	A multi-objective optimization algorithm	Hybrid energy storage topology composed of rechargeable batteries and UCs	Optimal hybrid energy storage system sizing of an example electric vehicle application
B, Haiat, et. al., 2023, [100]	A hybrid power management scheme/ Artificial neural networks-based control scheme	A robust power management strategy to guarantee the optimal power flow in electric vehicle.	Battery/SCs and Integrated PV hybrid topology for EVs.	Efficient in improving the energy management of the vehicle
Z. Song, et. al., [2018], [101]	An optimal component sizing energy management strategy	Pontryagin's minimum principle is utilized to solve the optimization problem.	Hybrid energy storage-based EV charging station	Cost reduction
A. Mehraban, et. al., 2021, [102]	An optimal control theory approach	A two-dimensional Pontryagin's minimum principle for solving the raised problem	Battery-flywheel energy topology for EV station	The dynamics could be handled from the filtering and energy interaction aspects
A.A. Mamun, et.al., 2019, [103]	An online intelligent energy management strategy/ Particle swarm optimization control framework	Pontryagin's minimum principle for a hybrid military vehicle	Hybrid energy storage topology composed of lithium-ion battery and supercapacitor	Reduction of fuel consumption by using particle swarm optimization
R. Zahedi, et. al., 2022, [104]	A genetic algorithm (GA) based energy management scheme/ Logic optimizing control scheme	Power split control parameters for a given driving cycle in a relatively short computation time	Plug-in hybrid electric vehicles topology	Provision of short computational burden and near-optimality for a wide variety of driving cycles

B. CROSS-COUPLING CHARACTERISTICS OF THE MMLC

The magnetic link in the MMLC creates a cross-coupling trait between the terminal ports. Therefore, the voltage regulation and power transmission of each single port are influenced by the phase shift value applied to the other ports. To achieve accurate control of each individual port in the MMLC, it is important to consider that in practice, the leakage inductance of each port may not be the same, despite having the same turns ratio. This can affect the desired control objective of the MMLC. Therefore, to ensure precise control of each port, the magnetic link needs to be decoupled.

In [33], a simplified estimation for decoupling the magnetic link of the MMLC has been proposed by calculating the difference of the phase shift values between each port. The proposed MMLC configuration in [82] solves the power flow de-coupling problem by using the independent control of each active bridge. The author presented a hardware-based model of the MMLC aimed at achieving de-coupled power flow. The model focuses on studying the inherent leakage inductance of the source port and utilizes the small-signal model of the MMLC to regulate the power flow. A control solution is proposed to mitigate the impact of power unbalance problems caused by the mismatch parameter within the MMLC [105]. This is achieved by analyzing the mismatched inductance values on each winding of the magnetic-linked. The controller then compensates the phase shift value based on the calculation of the power flow equation. Thus, the power transferred to each port has been balanced. The small-signal modeling method is used to design a PI controller for the MMLC with the help of the decoupling method [106]. Two de-coupling methods have been discussed in the literature [107] for power flow control of the MMLC, which can improve performance and reduce response time. In addition, another author proposes an asymmetrical configuration of the high-frequency transformer inside the MMLC to solve the mismatch problem of delivering equal power [108]. This approach involves the use of a group of interconnected inductors to uniformly distribute the current, thereby balancing the current flowing through each electronic switch. This helps to reduce power loss and improve efficiency on the magnetic link.

With the de-coupling mechanism, the performance of the MMLC can be significantly enhanced. It provides the capability of handling power flow on each output port with different power level. Hence, the de-coupling method will be addressed in this research with detail to control the MMLC.

V. DISCUSSION AND FUTURE RESEARCH NEED TO ADDRESS

Ongoing advancements in converter topology, control, and power management of MLPC technologies have prompted the research community, industry, and other sectors to explore these technologies as potential candidates for future renewables tied grid infrastructure. With the growing global interest in the transition to a zero-carbon economy, MLPC has been identified as one of the most important research topics in the areas of renewables-integrated emerging applications.

Overall, the review of the different aspects has shown that each type of MLPC topology modeling, MLPC-based hybrid energy system with power management strategy has unique advantages and disadvantages under considerably different working applications. The review has shown that the purpose of each technology together is to increase the system efficiencies, improve operating performance under variable loads and generation, and handle grid integration issues for on-grid systems.

Numerous studies have demonstrated that MLPC technology must be compared to the traditional power converter (TPC) based technologies in terms of lifetime, capital cost, and operating cost to assess systems lifecycle cost.

Applying MLPCs to a RESs-tied power grid can produce many challenges as RESs are highly sensitive to sudden variations in weather conditions (passing clouds in a PV system or wind gusts in a WT), sudden variations in load demands, and other factors (capital investment, maintenance, components level interaction, each components life cycle, degradation with time and performance, etc.).

Further, MLPC technologies are highly nonlinear since they require multiple flows when these technologies need to operate in a highly dynamic environment, especially for RESs integrated situations. In this regard, designing adaptive MLPC topology with appropriate PMA/PMS including advanced control decisions that guarantee a stable dynamic operation is required. However, it is very challenging to design the most suitable control methodology in terms of design simplicity, simple control loop, less computational complexity, and cost-effectiveness. Therefore, this is still a research question.

As a consequence, the researchers are still working on ‘‘what are the most suitable MLPCs topologies with PMA/PMS for utilizing renewable energy surplus to maintain power quality, security, and stability’’ and ‘‘how the MLPCs and its associated PMA/PMS can mitigate the intermittency of RESs and variability of loads for grid-connected applications’’. Therefore, more research works on MLPCs with optimal, highly dynamic, and high bandwidth novel PMA/PMS will be needed to propose for addressing the above-mentioned challenges.

VI. CONCLUSION

This paper has presented a comprehensive review as well as a more specific assessment of converter topology, control, and power management of MLPC technologies for interfacing renewable energy integration to the traditional power grid, more electric aircraft applications, electric vehicle charging implementation, etc. Because of their capability, MLPCs have been considered a promising interfacing option for low level to high level voltage applications. The various configuration details with an emphasis on various types of on-grid/off-grid (AC or DC) integrated MLPC systems have been discussed. Following this, various types of MLPCs topologies for low, medium, and high-voltage level applications have been discussed. Several modulation methods and approaches for modeling directions have also been discussed in detail. From the literature survey, it can be summarized that the selection of the most suitable topology of MLPCs with appropriate PMA/PMS for utilizing renewable energy is a critical research question. Furthermore, various types of advanced controls used in MLPCs-based MG/smart grid systems have been reviewed to show highly reliable, efficient, controllable, fault-tolerant, and cost-effective candidates. Finally, a critical review of existing PMS/PMA technologies against the fluctuation and uncertainty of RESs and loads has been discussed by emphasizing the need for efficient, reliable, and cost-effective operations to meet power quality, security, stability, as well as future EV prospects. The key aspects that require additional research for the MLPCs with PMS/PMA/controller technologies for the utilization of renewable energy in future EV applications have also been identified.

AUTHOR DECLARATION

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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