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A Comprehensive Review of Bidirectional DC-DC Converters: Topologies, Modelling, and Control Strategies

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Abstract **- This paper provides a review of bidirectional DC–DC converters, focusing on sophisticated topological structures, dynamic modelling techniques, and effective control methodologies for electric mobility, renewable energy integration, and energy storage. A comparative evaluation of isolated versus non-isolated designs reveals trade-offs related to efficiency, galvanic isolation, and voltage control. Various modelling strategies, such as state-space averaging, discrete-time analysis, and small-/large-signal methods, are examined for control-oriented design applications. Additionally, advanced control methods like PI control, fuzzy logic, sliding mode control, and model predictive control are analysed to improve transient response, system stability, and efficiency in bidirectional power flow.**

Keywords – Bidirectional DC-DC Converter, Modelling, Control Techniques, Stability, EV applications

I. INTRODUCTION

The various categories of non-isolated DC-DC converter [1] also highlight the challenges encountered by fuel cell technology and delineate its possible applications. Additionally, it offers an extensive classification of DC conversion circuits. Reversible DC-DC converters are extensively utilized in scenarios where galvanic isolation is unnecessary, including low-to-medium voltage storage systems, Green energy integration, and e-mobility solutions equipped with auxiliary electrical power grid. In contrast to isolated converters, these devices lack a high-frequency transformer, resulting in a design that is simpler, more compact, lighter, and more efficient. However, this absence also restricts their application in the systems that necessitate safety isolation or require very high voltage conversion ratios.

Electric vehicles (EVs) often utilize various Two-way DC converters such as buck–boost, SEPIC, and boost power conversion architectures. A particular type of power converter, known as the boost converter, elevates the voltage from a lower input level to a significantly higher output voltage. This component is extensively used in EVs due to its ability to effectively convert Electrochemical energy for driving electric motors Traditionally, the pulse width modulation(PWM) controls the boost converter, facilitating optimized efficiency and stable output electrical tension.
The configuration of Dual-directional DC converters is essential to the A thorough energy management system for electric vehicles. A bidirectional converter is a device used in power electronics. capable of transferring Electrical energy is transferred between two ports in both directions. It facilitates Sustainably utilized energy transfer conveying power from source to load, and enables the return of energy to the source.

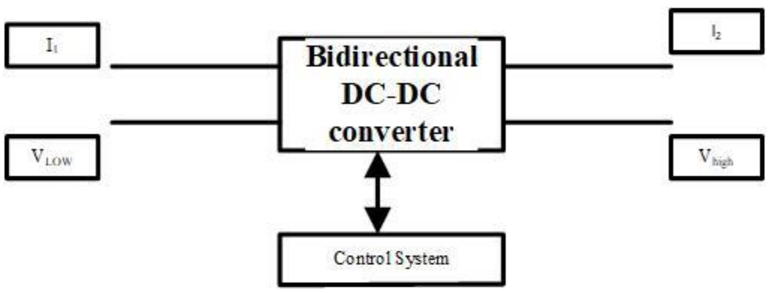

Fig.1. Structure of BDC.

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A Bidirectional DC Converter is a device that efficiently transforms electrical energy between two voltage sources, V_{Low} (low voltage) and V_{High} (high voltage), operating in either a boosting (step-up) or bucking (step-down) mode. It utilizes power electronic switches in conjunction with a control system to manage bidirectional energy flow, which is crucial for applications such as energy storage, electric vehicles, and green energy systems, as depicted in Fig.1. This versatility is vital in situations like electric vehicles, renewable energy systems, and battery storage, facilitating effective energy management, grid integration, and improved overall system efficiency. Bidirectional converters play a key role in modern energy systems by allowing for bidirectional power transfer and control.

An Isolated dual-directional DC converter serves as an electronic power conversion system interface that facilitates bidirectional power transfer between two DC sources while retaining galvanic isolation via a high-frequency transformer. This converter type is characterized by its high efficiency and versatility, enabling two-way voltage regulation conversion, making it ideal for scenarios that require both charging and discharging capabilities. The isolation feature enhances safety, provides noise immunity, and allows for the connection of systems with differing ground potentials. Among the various topologies available, the Two-stage active bridge stands out as Preeminent favoured due to its benefits of Reduced-stress switching, minimized switching losses, and superior productivity. Isolated bidirectional converters find extensive application in Electric vehicles, sustainable energy infrastructures, and energy storage technologies, and DC micro grids, where dependable, efficient, and safe power transfer is crucial. The various categories of Isolated DC voltage converter [2].

The mathematical modelling of a bidirectional DC energy conversion system is mainly done using techniques such as state-space averaging for dynamic analysis and small-signal linearization for control design. For transient and switching behaviour, switching function models are used, while discrete-time models are applied in digital control systems. In broader applications, large-signal models capture nonlinear dynamics, impedance-based methods ensure stability in interconnected systems, and energy-based modelling helps analyse power flow in EVs and renewable grids. These approaches provide a complete framework for design, analysis, and control of converters.

The formulation on control techniques for bidirectional DC power conversion systems, which include hysteresis, sliding mode, and Proportional Integral (PI) methods, is dependent on the particular requirements of the electric vehicle (EV) system. Hysteresis control, noted for its clarity and reliability, serves as a basic solution that refrains from necessitate a complex modelling of the converter using mathematical equations However, the present method does not match effectualness of the other control techniques, which may result in significant harmonic distortion.

II. BIDIRECTIONAL DC - DC CONVERTER TOPOLOGIES

A. Isolated Converters

i. ZVS-ZCS Bidirectional Full Bridge DC-DC Converter

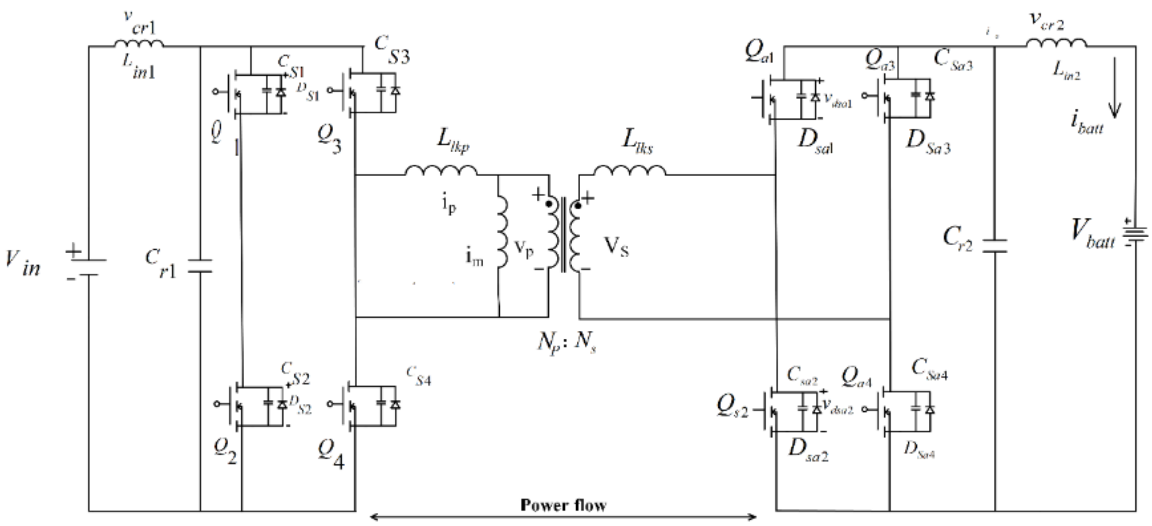

Fig.2. Proposed ZVS-ZCS Bidirectional Full-Bridge DC-DC Converter.

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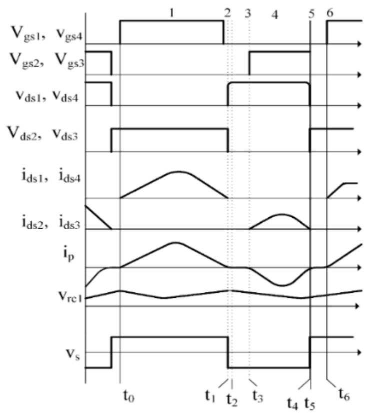

Fig.3. key waveforms during the buck / charge operation mode

A Bidirectional Full Bridge DC-DC Converter utilizing Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) is a power electronic configuration that facilitates efficient power transfer between two DC sources while minimizing switching losses. In this converter, both the primary and secondary bridges function with full-bridge arrangements, enabling bidirectional energy flow, which is particularly advantageous for applications such as electric vehicles, renewable energy systems, and energy storage solutions. ZVS guarantees that the switches activate when the voltage across them is nearly zero, thereby reducing turn-on losses and electromagnetic interference, whereas ZCS ensures that switches deactivate when the current flowing through them is nearly zero, thus minimizing turn-off losses. Collectively, these soft-switching methods enhance efficiency, alleviate stress on devices, and allow for higher switching frequencies in comparison to hard-switching converters. The bidirectional capability allows for seamless charging and discharging of energy storage systems, while the full-bridge design offers galvanic isolation via a high-frequency transformer, flexible voltage matching, and improved control over power flow. Fig.2 and Fig.3 Shows the circuit of ZVS-ZCS Bidirectional Full-Bridge DC-DC Converter and the relevant waveforms respectively [3].

Equation (1) shows the average output voltage of the circuit

$$V_{out}(\mathrm{t}) = \frac{N_S}{N_P}\ V_{rc}(\mathrm{t}) \qquad (1)$$

Here, V_{rc} = Resonant interaction of the leakage inductance and the resonant capacitor.

ii. A Bidirectional LLCL Resonant DC-DC Converter

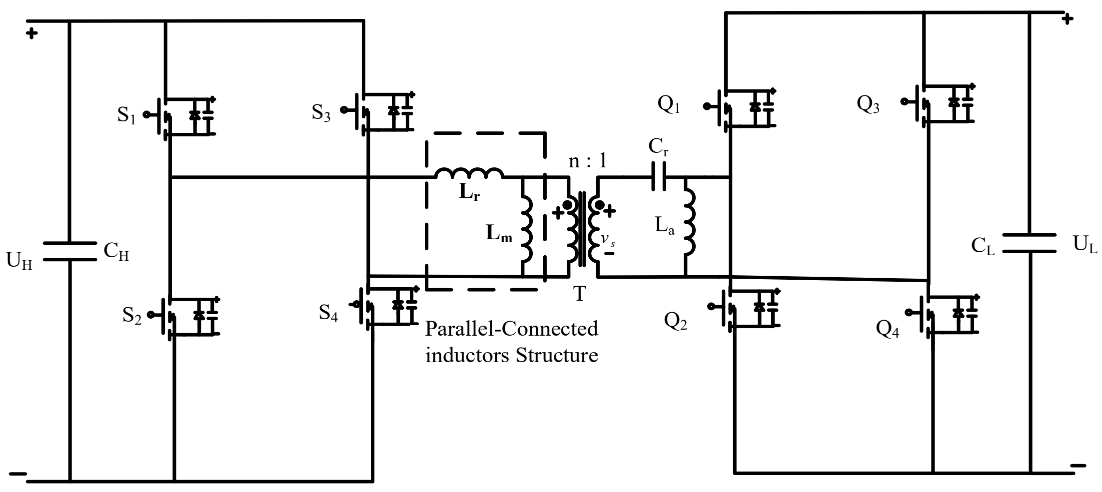

Fig.4. Overall topology of the proposed LLCL converter.

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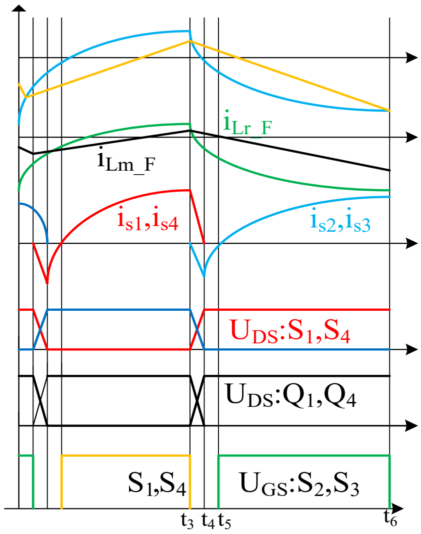

Fig.5. Key waveform in forward mode

A bidirectional LLCL resonant DC–DC converter represents a sophisticated topology aimed at achieving high efficiency and reliability in power conversion applications, including electric vehicles, renewable energy systems, and energy storage. By integrating an LLCL resonant network, this converter effectively diminishes the circulating resonant tank currents, which subsequently reduces conduction losses and enhances overall efficiency. furthermore, the design guarantees that the resonant capacitor endures significantly lower voltage stress in comparison to traditional resonant converters, thus improving the reliability and lifespan of the capacitor while permitting the use of components with lower ratings. This configuration also supports soft-switching operation for both the primary and secondary side switches across a broad load range, leading to decreased switching losses and enhanced power density. In addition, the bidirectional functionality of the converter allows for smooth power flow in both directions, rendering it exceptionally suitable for applications that necessitate efficient charging and discharging cycles. In summary, the LLCL resonant configuration offers an optimized equilibrium between efficiency, diminished stress on passive components, and robust bidirectional operation. Fig.4 and Fig.5 Shows the Circuit of bidirectional LLCL Resonant DC-DC Converter and the relevant waveforms respectively [4].

Equation (2) and (3) shows the voltage gain of the LLCC Resonant tank.

Forward mode (high voltage – low voltage)

$$U_L = M_F U_H \qquad (2)$$

With M_F the DC Voltage gain of the LLCC tank.

$$M_F = \frac{U_L}{U_H}$$

Backward mode (Low voltage – High voltage)

$$U_H = M_B U_L \qquad (3)$$

Here, U_L = Low side DC voltage

M_F = Forward-mode DC voltage gain of the LLCL resonant tank

U_H = High side DC voltage

M_B = Backward-mode DC voltage gain pf the LLCL resonant tank

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iii. Forward–Fly-Back Hybrid Bidirectional DC–DC Converter

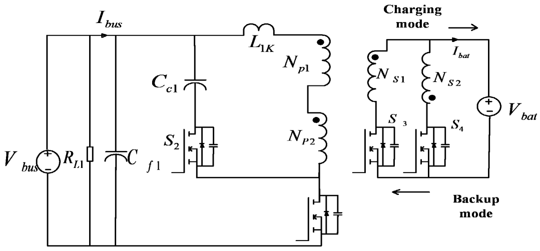

Fig.6. Proposed active-clamp forward–fly-back hybrid BDC

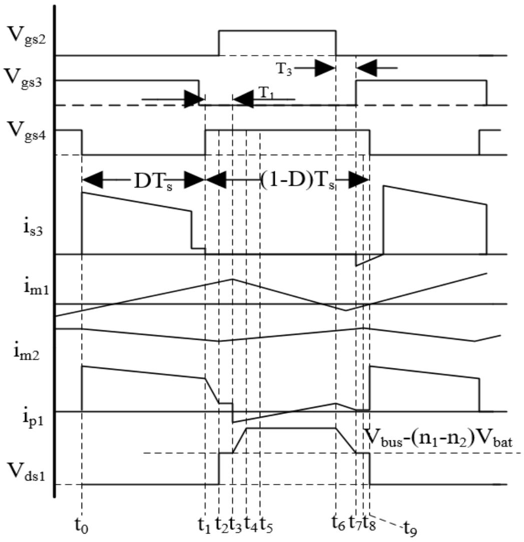

Fig.7. Key waveforms of active-clamp forward–fly-back hybrid BDC.

A Forward–Fly-back Hybrid Bidirectional DC–DC Converter represents a distinctive topology that merges the characteristics of both forward and fly-back converters to facilitate efficient bidirectional power flow. In this configuration, the forward converter function is mainly employed to transfer power in the forward direction with high efficiency, while the flyback operation enables energy transfer and voltage balancing during reverse power flow. By combining the benefits of both modes, this hybrid converter minimizes the number of components, guarantees galvanic isolation, and achieves a compact design with enhanced reliability. Furthermore, it provides superior voltage regulation, lower switching losses, and improved soft-switching capability, rendering it suitable for applications such as renewable energy systems, electric vehicles, battery charging and discharging, and other energy storage systems that necessitate bidirectional power flow. This hybrid methodology effectively balances performance. Fig.6 and Fig.7 Shows the Circuit of bidirectional LLCL Resonant DC-DC Converter and the relevant waveforms respectively [5].

Equation (4) shows the average output voltage of the proposed circuit.

$$V_{out} = \frac{(n_1 D + n_2(1-D))V_{in}}{D} \qquad (4)$$

Here, D = Duty ratio

V_{out} = Output Voltage

V_{in} = input voltage

n_1 = turns ratio of the forward transformer

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n_2 = turns ratio of the fly-back transformer

iv. Hybrid Switching Modulation of Isolated Bidirectional DC-DC Converter

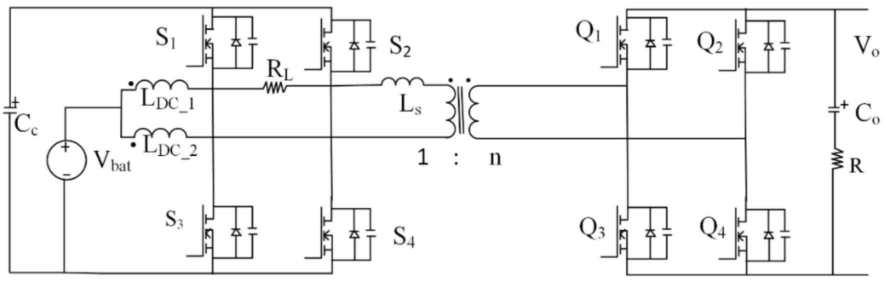

Fig.8. Current-fed isolated bidirectional DC-DC converter (CF-IBDC).

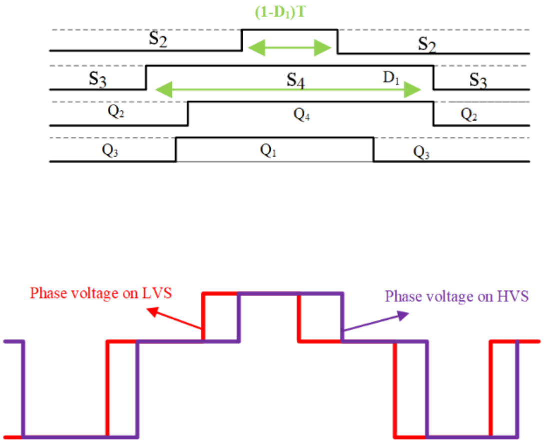

Fig.9. Proposed modulation strategy for the CF-IBDC.

A Hybrid Switching Modulation of an Isolated Bidirectional DC–DC Converter for energy storage systems in DC micro-grids represents a sophisticated control methodology aimed at improving the efficiency, reliability, and adaptability of power transfer between the storage unit and the grid. This technique integrates various switching strategies, including phase-shift modulation and duty-ratio control, to enhance converter performance across different load and voltage scenarios. The hybrid modulation facilitates soft-switching operation, diminishes circulating current, and reduces switching losses, thus elevating the overall system efficiency. Moreover, it improves dynamic response, offers superior voltage regulation, and enables seamless bidirectional power flow for both charging and discharging of the energy storage system. Consequently, this approach is exceptionally well-suited for DC micro-grid applications, where it is essential to maintain stability, efficiency, and power quality for the integration of renewable energy sources and the reliable operation of distributed energy systems. Fig.8 and Fig.9 Shows the Circuit of Hybrid Switching Modulation of Isolated Bidirectional DC-DC Converter and the relevant waveforms respectively [6].

Equation (5) shows the average output voltage of the proposed circuit.

$$V_{Out} = \frac{nV_{bat}}{1 - D_1} \qquad (5)$$

Here, V_{bat} = Battery Voltage

D_1 = Duty ratio

n = transformer turns ratio

V_{Out} = high voltage DC bus output

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v. Push-Pull Current Type Bidirectional DC/DC Converter

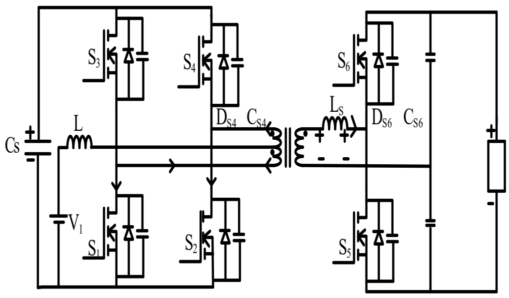

Fig.10. Topology of push pull current type bidirectional DC/DC converter.

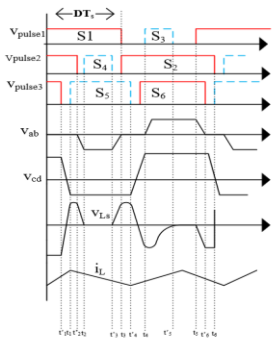

Fig.11. Key waveforms of the converter in a switching cycle.

A bidirectional DC–DC converter of the push–pull current-type is a configuration that facilitates efficient two-way power transfer while ensuring galvanic isolation via a centre-tapped transformer. In this setup, two switches alternately conduct to operate the transformer in push–pull mode, which guarantees balanced operation and optimal use of the transformer core. The current-type characteristic of the converter permits direct current regulation, thereby decreasing stress on the switching devices and enhancing reliability. This topology also accommodates bidirectional operation, allowing power to flow from the source to the load or vice versa, making it particularly suitable for applications such as battery charging and discharging, renewable energy integration, and electric vehicles. The converter presents benefits such as high efficiency, a reduced number of components, and the capability to manage high power levels with commendable dynamic response. Its symmetrical operation reduces transformer saturation and improves system stability, rendering it a compelling option for contemporary bidirectional power conversion systems. Fig.10 and Fig.11 Shows the Circuit of Push-Pull Current Type Bidirectional DC-DC Converter and the relevant waveforms respectively [7].

Equation (6) shows the average output voltage of the proposed circuit.

$$V_2 = \frac{n}{1-D} V_1 \qquad (6)$$

Here, V_2= Secondary Voltage

V_1= Primary Voltage

n = no. of turns

D = Duty Cycle

vi. Highly Efficient Isolated Multiport Bidirectional DC/DC Converter for PV Applications

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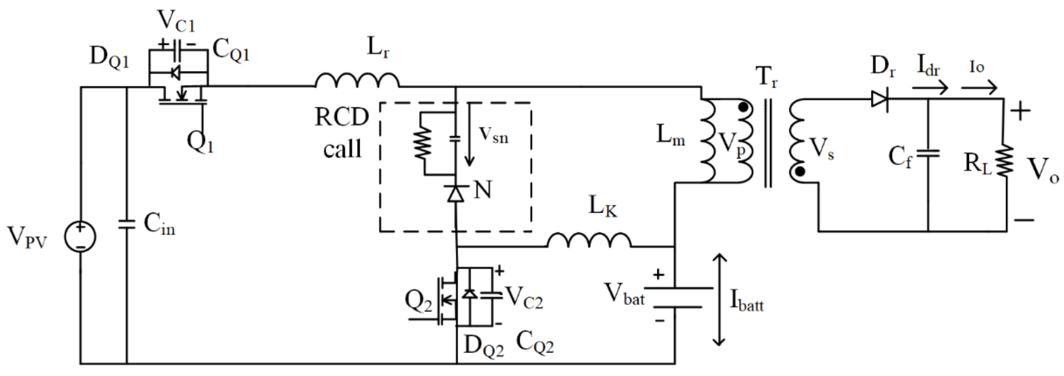

Fig.12. The proposed battery charger topology.

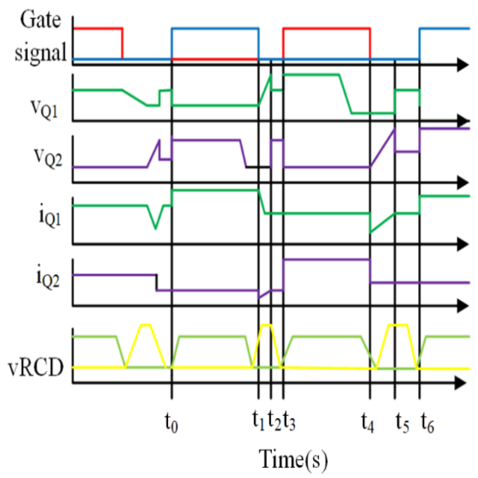

Fig.13. Steady state voltage and current waveform.

A highly efficient isolated multiport bidirectional DC–DC converter designed for photovoltaic applications, utilizing the fly-back topology, aims to integrate various power sources and storage units with enhanced energy management. In this setup, the fly-back converter offers both galvanic isolation and bidirectional power flow, facilitating smooth energy transfer between photovoltaic panels, energy storage systems, and the DC bus. The multiport design decreases the necessity for multiple dedicated converters, thus reducing cost, size, and complexity. Its bidirectional functionality allows for effective charging and discharging of energy storage while ensuring stable power delivery to the load. By implementing advanced control strategies, the converter attains high efficiency, lower switching losses, and better voltage regulation across various operating conditions. This makes it exceptionally suitable for PV-based renewable energy systems, where efficient energy harvesting, storage management, and reliable integration into DC micro-grids are essential for optimal system performance. Fig.10 and Fig.11 Shows the Circuit of Highly Efficient Isolated Multiport Bidirectional DC-DC Converter and the relevant waveforms respectively [8].

Equation (7) shows the average output voltage of the proposed circuit.

$$V_{Out} = V_{PV} * n * \frac{t_{on}}{T_S - t_{on}} \qquad (7)$$

Here, V_{Out} = Output DC bus voltage

V_{PV} = PV input voltage

n = transformer turs ratio

t_{on} = Switch on-time

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T_S = Switching period

vii. Bidirectional Dual Active Bridge DC-DC Converter

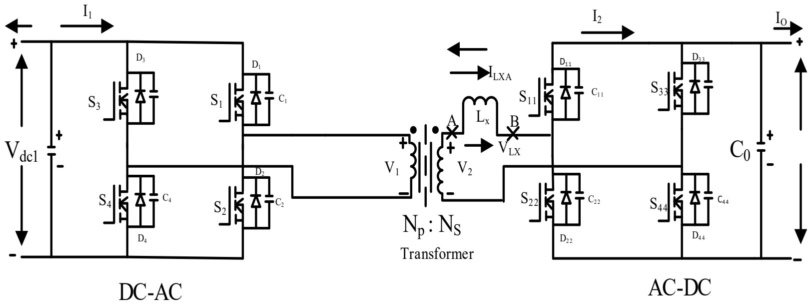

Fig.14. Bidirectional Dual Active Bridge DC-DC Converter.

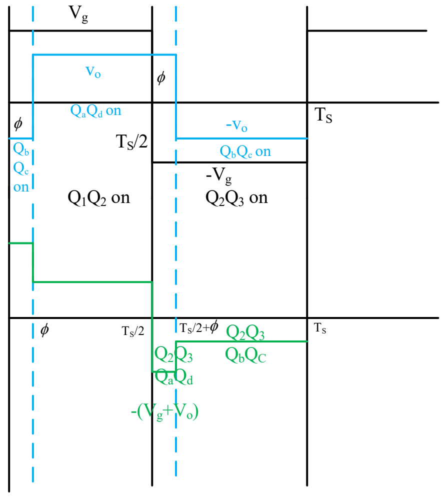

Fig.15. Key Waveform of Gate signals, Inductor current and voltage, Load current

A Bidirectional Dual Active Bridge (DAB) DC–DC converter represents a highly efficient isolated power conversion topology that facilitates the bidirectional flow of energy between two DC sources. It comprises two full-bridge converters connected via a high-frequency transformer, which ensures galvanic isolation and aids in voltage matching across different levels. by employing phase-shift control between the primary and secondary bridges, the DAB converter effectively regulates power transfer while achieving soft-switching conditions such as Zero Voltage Switching (ZVS), thereby reducing switching losses and improving efficiency. Its bidirectional functionality renders it particularly suitable for applications in renewable energy systems, energy storage integration, electric vehicles, and DC micro-grids, where both charging and discharging operations are necessary. The modular design, high power density capability to accommodate wide voltage variations position the DAB converter as a promising solution for contemporary power electronic systems. Fig.14 and Fig.15 Shows the Circuit of Bidirectional Dual Active Bridge DC-DC Converter and the relevant waveforms respectively [9].

Equation (8) shows the average output voltage of the proposed circuit.

$$V_{out} = D*n*V_{in} \qquad (8)$$

Here, V_{out} = Output Voltage

D = Duty ratio

V_{in} = Input Voltage

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n = no. of turns

B. Non-Isolated Converters

ix. Non-isolated bidirectional DC–DC converter

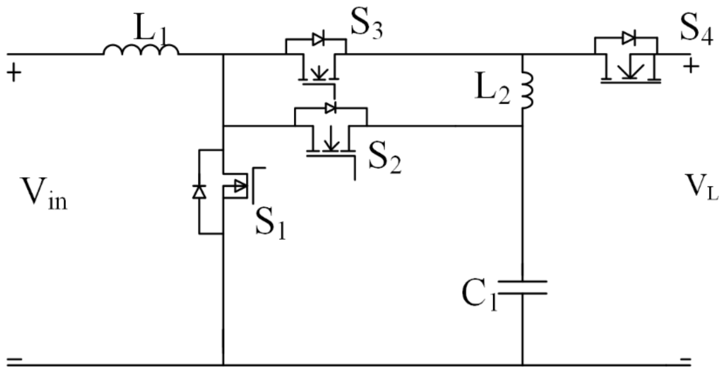

Fig16. proposed Bidirectional DC-DC Converter

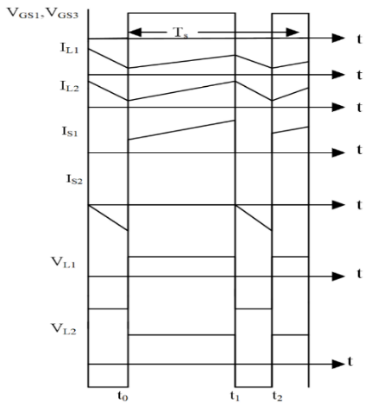

Fig17. Typical waveform of proposed converter in CCM.

A non-isolated bidirectional DC–DC converter (NIBDC) is a power electronic configuration that facilitates energy transfer in both directions between two DC sources without requiring a galvanic isolation transformer. It generally integrates the characteristics of both buck and boost converters, allowing for step-down and step-up voltage conversion based on the direction of power flow. In buck mode, energy is transferred from the high-voltage side to the low-voltage side, whereas in boost mode, it functions in the opposite direction to elevate the voltage level. Due to their straightforward design, compact dimensions, and fewer components, NIBDCs provide high efficiency and lower costs in comparison to isolated converters. Nonetheless, they do not offer electrical isolation, which restricts their application in safety-sensitive or high-voltage scenarios. These converters are extensively utilized in renewable energy systems, battery energy storage, electric vehicles, and DC micro-grids, where bidirectional power management, compact design, and high efficiency are crucial. Fig.16 and Fig.17 Shows the Circuit of Non-isolated bidirectional DC–DC converter DC-DC Converter and the relevant waveforms respectively [10].

Equation (9) and (10) shows the average output voltage of the proposed circuit

Step up mode

$$V_H = \frac{V_L}{(1-D)^2} \qquad (9)$$

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Step down mode

$$V_L = D^2 * V_H \qquad (10)$$

Here, V_H = High side (input) Voltage

V_L = Low side (output) Voltage

D = Duty ratio

x. A Non-Isolated Hybrid-Modular DC-DC Converter

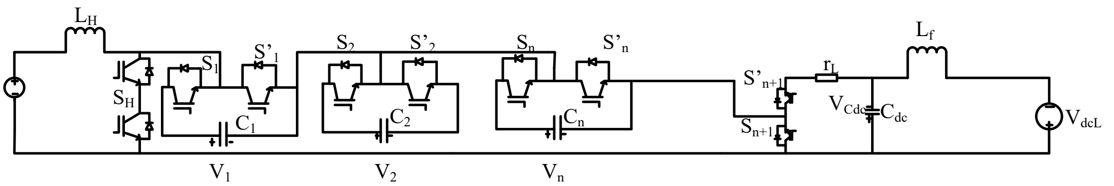

Fig.18. The self-balanced hybrid-modular DC-DC converter.

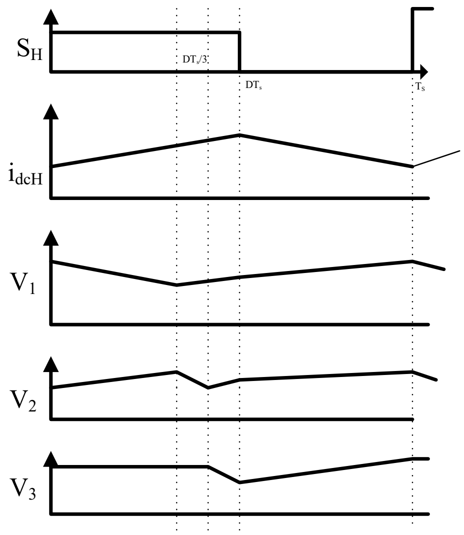

Fig.19. Waveform of Proposed System.

A non-isolated hybrid-modular DC-DC converter designed for DC grids integrates the benefits of modular architecture and hybrid functionality to achieve superior efficiency, scalability, and effective power management in contemporary DC distribution networks. The hybrid-modular design enables several converter modules to function in parallel, thereby improving flexibility and fault tolerance while ensuring stable power transfer. Small-signal modelling is utilized to thoroughly examine the dynamic behaviour of the converter, offering valuable insights into control-to-output characteristics, input-output voltage relationships, and stability across various operating conditions. Drawing from this modelling, a robust control strategy is formulated to manage the output voltage, distribute current among modules, and guarantee reliable performance amidst load fluctuations and grid disturbances. Consequently, the proposed converter architecture is exceptionally well-suited for the integration of renewable energy sources, energy storage systems, and advanced DC micro-grids, where efficiency, stability, and modular expandability are of utmost importance. Fig.18 and Fig.19 Shows the Circuit of Non-Isolated Hybrid Modular bidirectional DC–DC converter DC-DC Converter and the relevant waveforms respectively [11].

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Equation (11) and (12) shows the average output voltage of the proposed circuit

Relation between battery voltage and super capacitor

$$V_{sc} = \frac{V_B}{1 - D_1} \qquad (11)$$

Relation between Super capacitor voltage and intermediate capacitor

$$V_{C1} = \frac{V_{SC}}{1 - D_2} \qquad (12)$$

V_{sc} = Voltage at super capacitor

V_{C1} = voltage at capacitor C_1

D = Duty Cycle

xi. Non-isolated stacked bidirectional soft-switching DC-DC converter

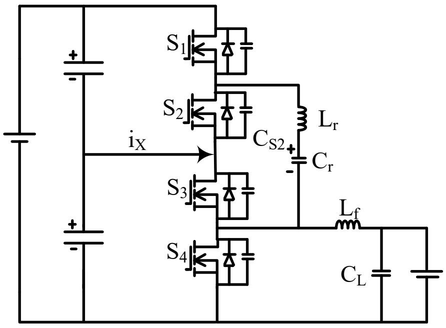

Fig.20. Stacked bidirectional converter

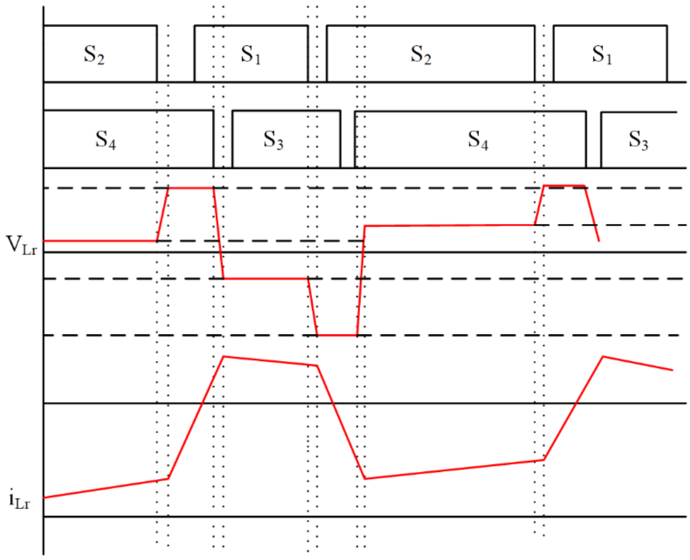

Fig.21. Steady-state waveforms of stacked converter

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A non-isolated stacked bidirectional soft-switching DC-DC converter represents a power conversion topology that is engineered to facilitate efficient bidirectional power transfer between two DC sources. This technology is commonly utilized in energy storage systems, electric vehicles, and DC micro-grids. The designation "stacked" pertains to its arrangement, wherein multiple converter cells are interconnected in a stacked configuration to manage elevated voltage and current levels while distributing stress across the devices. Given its non-isolated nature, there is an absence of galvanic isolation, which simplifies the design, enhances compactness, and improves efficiency in comparison to isolated topologies. The bidirectional capability permits the converter to function in both charging (buck mode) and discharging (boost mode) operations, rendering it appropriate for battery charging and discharging applications. To optimize performance, soft-switching methodologies such as Zero-Voltage Switching (ZVS) or Zero-Current Switching (ZCS) are employed. These strategies diminish switching losses, lessen electromagnetic interference (EMI), and bolster overall efficiency, particularly at elevated switching frequencies. During operation, the stacked architecture facilitates voltage sharing, current balancing, and a reduction in voltage stress across semiconductor switches. This characteristic is advantageous for scaling the converter for medium- and high-power applications. The converter is characterized by high efficiency, a compact design, and enhanced reliability, making it ideally suited for the integration of renewable energy, electric mobility, and smart grid systems. Fig.20 and Fig.21 Shows the Circuit of Non-Isolated stacked bidirectional soft-switching DC-DC converter and the relevant waveforms respectively [12].

Equation (13) shows the average output voltage of the proposed circuit

$$M = \frac{V_L}{V_H} = \frac{D}{2} \qquad (13)$$

Here, M = Voltage conversion ratio

V_L = Low Voltage side

V_H = High voltage side

II. MODELLING TECHNIQUE

i. State-Space Average Model

The State-Space Average Model is developed to mathematically represent the dynamic behaviour of the bidirectional DC-DC converter by averaging the circuit equations over one switching period. Since the converter changes its topology depending on the ON and OFF states of the switches, separate state equations are first derived for each switching interval using inductor current and capacitor voltage as the state variables. These equations are then combined through duty cycle–based averaging, resulting in a unified state-space model that captures the average dynamics of the system. By applying perturbation and linearization techniques, the averaged model is further extended to obtain the small-signal AC model, which is useful for control design and stability analysis. This modelling approach simplifies the complex switching behaviour into continuous equations, making it easier to design controllers and predict converter performance under different operating modes [13].

ii. Discrete-time modelling

Discrete-time modelling for a bidirectional DC-DC converter is a technique that represents the converter's dynamic behaviour at specific switching instants rather than averaging over a cycle. In this approach, the state variables such as inductor/transformer current and capacitor voltage are expressed in discrete steps, corresponding to each sub-interval of a switching period. This captures both fast dynamics (like current ripple) and slow dynamics (like output voltage variation), which are often lost in continuous-time averaged models. For bidirectional converters such as the dual active bridge (DAB), discrete-time modelling is particularly useful because the transformer current averages to zero over a cycle, making classical averaging inaccurate. the dynamics of the dual active bridge (DAB) DC-DC converter by assessing the state variables—primarily transformer current and capacitor voltage—during each switching sub-interval rather than depending on averaged models [14].

iii. Small-signal analysis

Small-signal analysis is conducted to derive a control-oriented model of the isolated bidirectional battery charger. The large-signal averaged state-space model that was initially created outlines the overall dynamics of the converter; however, it primarily relies on the DC link and battery voltages, which are not directly affected by the control variable. Consequently, to adapt the model for controller design, the system is linearized around a specific operating point, and variations in the duty cycle are introduced. This process results in the small-signal model, where the fluctuation in the duty cycle serves as the input variable, and the resulting

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equations establish the connection between control perturbations and system response. The analysis verifies that the small-signal model accurately reflects the transient behaviour of the converter, as confirmed by simulations and experimental findings [15].

iv. Large signal modelling

The large-signal model is particularly useful for studying steady-state performance and transient responses of the converter in both buck and boost modes. It allows evaluation of how the system behaves under different operating conditions, such as during power transfer between the medium-voltage DC bus and low-voltage storage, or under disturbances like load changes. However, because the large-signal model does not directly express dynamics in terms of the control variable (duty cycle), it is less suited for controller design. Instead, it provides the foundation from which small-signal models are derived for control-oriented analysis [16].

IV. CONTROL TECHNIQUES

i. Proportional-Integral (PI) Controller

The Proportional-Integral (PI) controller merges proportional and integral control strategies, providing a more effective solution by overcoming the shortcomings of both. Fig.22. Shows the Block diagram of PI Controller. Proportional controllers produce an output that is directly related to the error signal, while integral controllers react to the accumulation of the error signal over time. By integrating both methods into a PI controller, stability is enhanced, helping to minimize steady-state error. The mathematical formulation of the PI controller includes both the proportional and integral components, which helps to mitigate the potential instability issues linked with integral controllers. The transfer function of the controller, represented in Laplace transforms, highlights its ability to substantially decrease steady-state error while maintaining system stability.

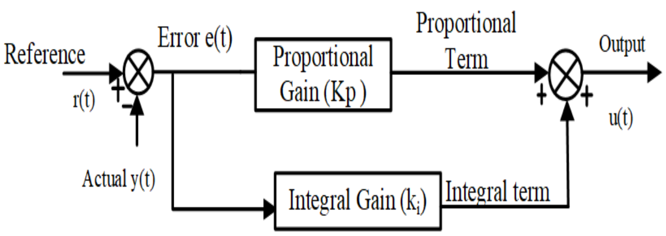

Fig.22. Block diagram of PI Controller.

The suggested control strategy excels in handling the nonlinear dynamics and distinctive features of boost converters, ensuring stable and accurate control. The complexities associated with Continuous Conduction Mode operation are effectively addressed by integrating cascade PI control with Model Reference Adaptive Control. characteristics. Simulations conducted in MATLAB/Simulink demonstrated the control system's accuracy and robustness, showcasing a quick response, minimal overshoot, and precise tracking. This confirmed the practical effectiveness of the proposed approach. The use of cascade control and MRAC methods presents a promising solution for improving the performance and stability of boost converter systems [17], [18], [19], [20].

ii. Fuzzy Logic Controller

Fuzzy logic control in DC converters serves the purpose of managing the converter's duty cycle by taking into consideration incoming factors like the present voltage magnitude and the desired voltage. Fig.23. Shows the Block diagram of Fuzzy Logic Controller. Fuzzy logic was the method used to achieve this.

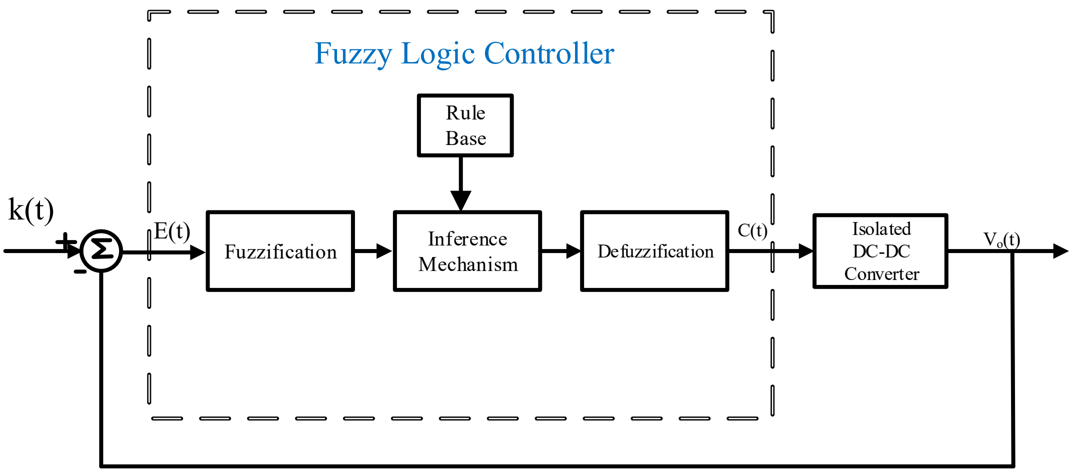

Fig.23. Block diagram of Fuzzy Logic Controller.

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A fuzzy logic controller (FLC) is employed in a bidirectional DC-DC converter to facilitate intelligent and robust management of power exchange between two DC sources, such as a battery and a DC bus. In contrast to standard PI or PID controllers that depend on accurate mathematical models, the fuzzy logic controller uses linguistic rules and approximate reasoning, making it more adept at dealing with nonlinearities, parameter variations, and uncertainties that are characteristic of power converters. By taking the error and the rate of change of error as input variables, the FLC produces control signals that adjust the duty cycle, thus ensuring stable voltage or current across diverse operating conditions. It guarantees efficient energy transfer in both buck (charging) and boost (discharging) modes while permitting smooth transitions between the two. Furthermore, the FLC enhances dynamic performance, reduces overshoot, and lessens steady-state error, which boosts the overall dependability of the converter in the face of varying load and source conditions. Therefore, incorporating fuzzy logic control in bidirectional DC-DC converters leads to improved adaptability, quicker regulation, and greater robustness when compared to traditional control methods.

iii. Sliding Mode Control

Sliding Mode Control (SMC) is crucial in managing bidirectional DC–DC converters due to its resilience, rapid dynamic response, and capability to address system nonlinearities and variations in parameters. Fig.24. Shows the Block diagram of Sliding Mode Controller. In a bidirectional DC–DC converter, power can flow in two directions (buck mode and boost mode), and the system faces disturbances like load changes, fluctuations in input voltage, and uncertainties in switching. Conventional linear controllers frequently find it challenging to sustain stable operation in such scenarios. As a nonlinear control approach, SMC compels the system states to converge and stay on a designated sliding surface, indifferent to disturbances and variations in parameters. This guarantees consistent voltage regulation, dependable current management, and robust bidirectional power transfer. Furthermore, SMC's reduced sensitivity to inaccuracies in the model makes it ideal for practical applications in energy storage systems, electric vehicles, and renewable energy systems where bidirectional converters are commonly utilized. Nevertheless, a significant drawback is the potential occurrence of chattering, which must be mitigated through enhanced designs such as higher-order SMC or boundary layer methods.

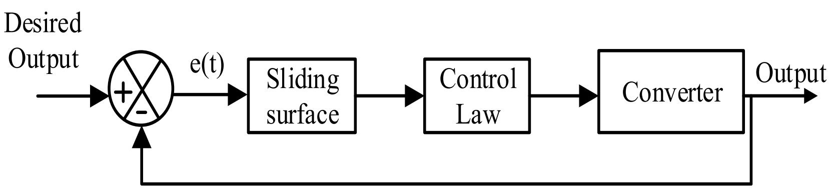

Fig.24. Block diagram of Sliding Mode Controller.

Due to the possible influence of measurement noise and changes in system parameters, sliding-mode control might need modifications to the control parameters to ensure stability [21]. Sliding mode control serves as an efficient control strategy utilized in BDC (buck-boost) converters for electric vehicles (EVs). This control technique seeks to maintain the load voltage within a specified range by establishing a sliding surface that directs the system's dynamics. The sliding mode control algorithm adapts the duty cycle of the converter's power switches in real-time and consistently tracks the difference between the target and actual output voltages.

iv. Partial Swarm Optimization (PSO) with Sliding Mode Control (SMC)

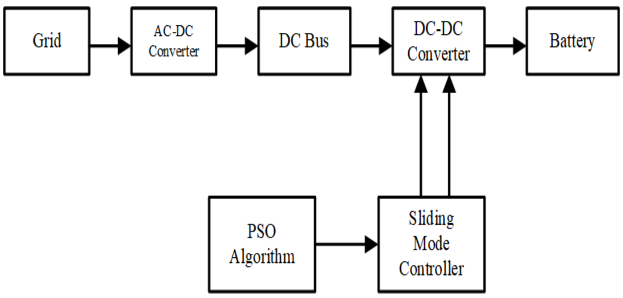

Fig.25. Block diagram of Partial Swarm Optimization (PSO) with Sliding Mode Control (SMC).

The implementation of PSO is feasible in a bidirectional DC-DC converter that employs established control techniques, such as SMC, as shown in Fig.25. In this instance, we have explored its application in electric vehicles to facilitate efficient and well-regulated battery charging. The choice of SMC control parameters is supported by the application of PSO. The combination of PSO

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and SMC aims to enhance control actions. PSO is designed to minimize an objective function that includes errors related to inductor current, DC bus voltage, and battery voltage. During each iteration, PSO evaluates the objective function, retaining the best particle value for comparison to find the ultimate global optimum among the best values within the SMC framework [22].

v. Model Predictive Control

The control technique utilizes a mathematical model to forecast future behaviours. It can be applied to manage Battery DC converters (BDCs), particularly those linking renewable energy sources to the grid, by estimating the upcoming state of the system based on the current control actions and the existing state of the system. Model Predictive Control (MPC) is capable of addressing system constraints, such as limits on voltage and power, as well as accommodating multiple inputs and outputs, and various objectives like maximizing power flow while reducing losses. This approach is an effective tool for managing BDCs due to its ability to tackle system constraints and handle multiple objectives simultaneously. The effectiveness of the proposed control method for battery applications and Model Predictive Control has been validated through simulation results. An activation control strategy was introduced as an optimal solution to manage and regulate the different operating modes of the battery, which include charging, discharging, and idling.

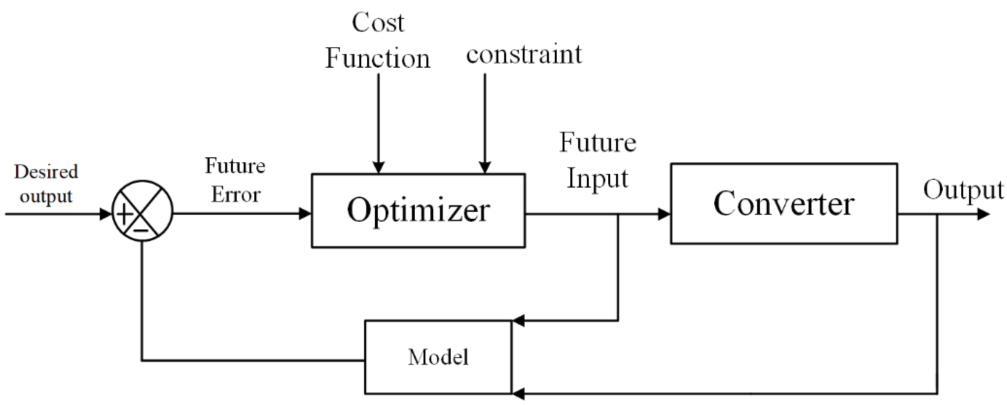

Fig.26. Block diagram of Model Predictive Control (MPC).

As the converters are built, each of these three modes operates independently. Neural networks facilitate the simplification and implementation of predictive controllers in power electronics in a cost-efficient way, and the resulting process flow diagram aids in visualizing and comprehending the control of BDCs, as illustrated in Fig.26. A comprehensive analysis was performed on the neural network architecture, shedding light on the specifics of the training and validation processes.

VI. PHASE SHIFT CONTROL

Phase-shift control modifies the phase synchronization between the input voltage and the coil current in DC converters to manage the output voltage. This methodology includes three key components. Single-phase shift (SPS) control focuses on synchronizing the phase shift between the inductor current and the input voltage. This method restricts output voltage control while simplifying implementation by maintaining a constant duty cycle and switching frequency. The suggested configuration uses a cascaded approach employing a proportional-resonant compensator for the 5LC along with a single-phase shift technique for the dual active half-bridge converter (DAHBC). Based on the comparative analysis, the proposed topology outperformed the existing designs regarding balanced power losses, reduced switch stress, and increased efficiency.

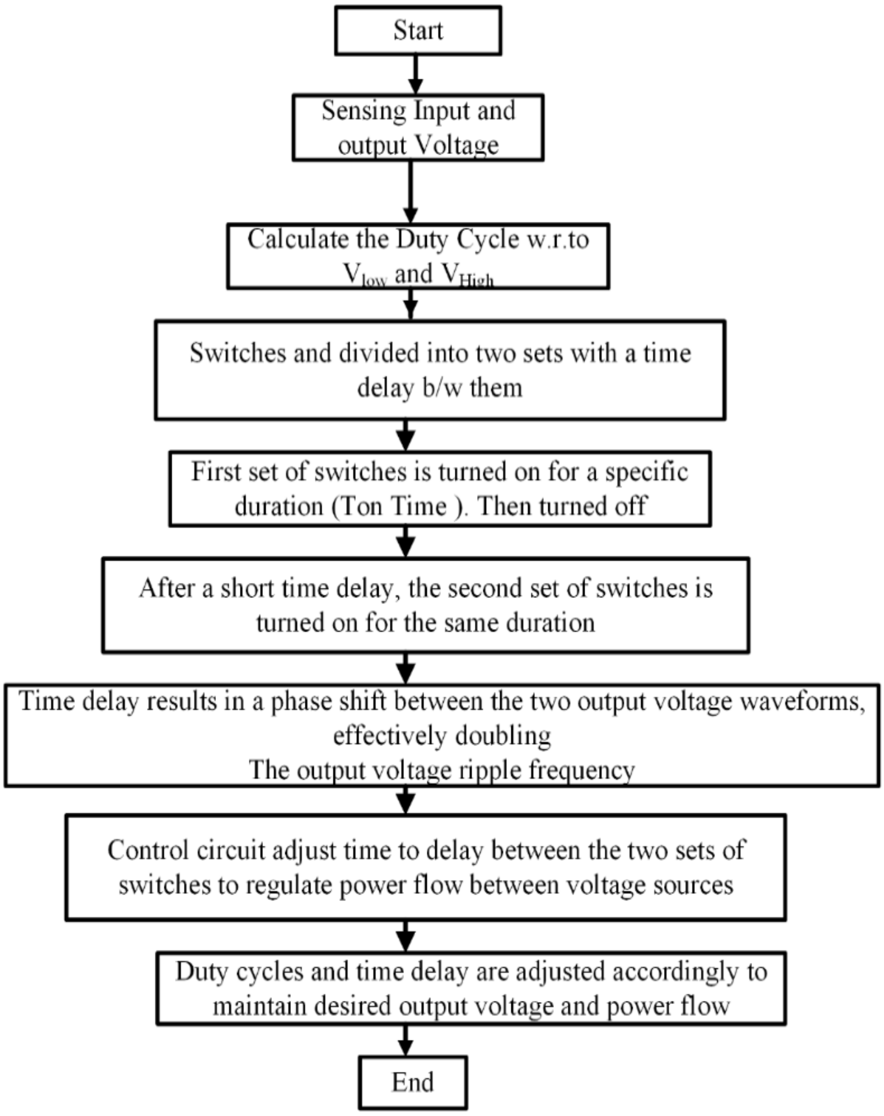

Fig.27. Flow Chart of Phase Shift Control.

and improved power quality throughout the operational modes [23]. A dual-phase shift (DPS) consists of introducing two separate phase alterations to the input voltage to improve output voltage management. It increases efficiency and regulation. Electric vehicle (EV) charging achieves greater efficiency by utilizing a Variable Switching Frequency (VSF) along with phase shifts. This approach optimizes power delivery and minimizes losses. Dynamically adjusting the switching frequency and phase shifts during the charging process decreases power losses and enhances energy transfer efficiency [24]. It effectively doubles the output voltage ripple frequency and allows for accurate power-flow regulation.

CONCLUSION

Bidirectional DC–DC converters (BDCs) be key to contemporary energy systems, especially in electric vehicles, renewable energy integration, and energy storage applications. Both isolated and non-isolated topologies, which include full-bridge, resonant, hybrid, modular, and dual active bridge configurations, facilitate efficient bidirectional power transfer. The implementation with soft-switching strategies such as ZVS and ZCS greatly minimizes dynamic losses, boosts efficiency, and enables high-frequency operation. Moreover, sophisticated modelling techniques—state-space averaging, small-signal, large-signal, and discrete-time methods—provide precise insights for control design. Intelligent controllers, including PI, fuzzy logic, sliding mode, model predictive, and phase-shift control, enhance stability, dynamic performance, and robustness. In summary, the combination of optimized converter topologies with advanced control strategies guarantees reliable and efficient bidirectional power flow, positioning BDCs as essential components for future sustainable power and mobility solutions.

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REFERENCES

[1] [1] Bhaskar, Mahajan Sagar, et al. "Survey of DC-DC non-isolated topologies for unidirectional power flow in fuel cell vehicles." Ieee Access 8 (2020):178130-178166.

[2] [2] S Chen, G Zhang, SY Samson, Y Mei, Y Zhang, " A review of isolated bidirectional DC-DC converters for data centres," Chinese Journal of Electrical Engineering, 2023, doi: 10.23919/CJEE.2023.000034.

[3] [3] C. -L. Chu and Y. Chen, "ZVS-ZCS bidirectional full-bridge DC-DC converter," *2009 International Conference on Power Electronics and Drive Systems (PEDS)*, Taipei, Taiwan, 2009, pp. 1125-1130, doi: 10.1109/PEDS.2009.5385685.

[4] [4] X. Ma, P. Wang, H. Bi and Z. Wang, "A Bidirectional LLCL Resonant DC-DC Converter with Reduced Resonant Tank Currents and Reduced Voltage Stress of the Resonant Capacitor," in *IEEE Access*, vol. 8, pp. 125549-125564, 2020, doi: 10.1109/ACCESS.2020.3007638.

[5] [5] F. Zhang and Y. Yan, "Novel Forward–Flyback Hybrid Bidirectional DC–DC Converter," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 5, pp. 1578-1584, May 2009, doi: 10.1109/TIE.2008.2009561.

[6] [6] H. -J. Choi, K. -W. Heo and J. -H. Jung, "A Hybrid Switching Modulation of Isolated Bidirectional DC-DC Converter for Energy Storage System in DC Microgrid," in *IEEE Access*, vol. 10, pp. 6555-6568, 2022, doi: 10.1109/ACCESS.2021.3138988.

[7] [7] X. Meng, C. Zhang, J. Feng and Z. Kan, "Analysis of Soft Switching Conditions for Push-Pull Current Type Bidirectional DC/DC Converter," in *IEEE Access*, vol. 12, pp. 59386-59398, 2024, doi: 10.1109/ACCESS.2024.3391608.

[8] [8] H. Mahfouz Ibrahim Saleeb *et al*., "Highly Efficient Isolated Multiport Bidirectional DC/DC Converter for PV Applications," in *IEEE Access*, vol. 12, pp. 114480-114494, 2024, doi: 10.1109/ACCESS.2024.3442711.

[9] [9] Deepti, T., et al. "Development and efficiency analysis of dual active bridge converter employing SiC devices using TMS 320F280039." *IET Circuits, Devices & Systems* 2025.1 (2025): 6336609.

[10] [10] Ardi, Hossein, Rouzbeh Reza Ahrabi, and Sajad Najafi Ravadanegh. "Non-isolated bidirectional DC–DC converter analysis and implementation." IET Power Electronics 7.12 (2014): 3033-3044.

[11] [11] Elserougi, Ahmed, et al. "A non-isolated hybrid-modular DC-DC converter for DC grids: Small-signal modeling and control." *IEEE Access* 7 (2019): 132459-132471.

[12] [12] Y. Mei, Q. Jiang, H. Yang, W. Li, X. He and S. Li, "Non-isolated stacked bidirectional soft-switching DC-DC converter with PWM plus phase-shift control scheme," in *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 4, pp. 631-641, July 2017, doi: 10.1007/s40565-017-0266-3.

[13] [13] M. S. M. Sarif, T. X. Pei and A. Z. Annuar, "Modeling, design and control of bidirectional DC-DC converter using state-space average model," *2018 IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, Penang, Malaysia, 2018, pp. 416-421, doi: 10.1109/ISCAIE.2018.8405509.

[14] [14] M. T. Iqbal, A. I. Maswood, M. Tariq, A. Iqbal, V. Verma and S. Urooj, "A Detailed Full-Order Discrete-Time Modeling and Stability Prediction of the Single-Phase Dual Active Bridge DC-DC Converter," in *IEEE Access*, vol. 10, pp. 31868-31884, 2022, doi: 10.1109/ACCESS.2022.3151809.

[15] [15] E. L. Carvalho, E. Carati, J. P. da Costa, C. M. O. de Stein and R. Cardoso, "Small-Signal Modeling and Analysis of an Isolated Bidirectional Battery Charger," *2018 13th IEEE International Conference on Industry Applications (INDUSCON)*, São Paulo, Brazil, 2018, pp. 439-445, doi: 10.1109/INDUSCON.2018.8627309.

[16] [16] -Y. Chung *et al*., "Integration of a bi-directional dc-dc converter model into a large-scale system simulation of a shipboard MVDC power system," *2009 IEEE Electric Ship Technologies Symposium*, Baltimore, MD, USA, 2009, pp. 318-325, doi: 10.1109/ESTS.2009.4906531.

[17] [17] J. Park, H. Kim, K. Hwang, and S. Lim, ''Deep reinforcement learning based dynamic proportional-integral (PI) gain auto-tuning method for a robot driver system,'' IEEE Access, vol. 10, pp. 31043–31057, 2022, doi: 10.1109/ACCESS.2022.3159785.

[18] [18] M. H. Qais, H. M. Hasanien, and S. Alghuwainem, ''A grey wolf optimizer for optimum parameters of multiple PI controllers of a grid connected PMSG driven by variable speed wind turbine,'' IEEE Access, vol. 6, pp. 44120–44128, 2018, doi: 10.1109/ACCESS.2018.P2864303.

[19] [19] K. Y. Ahmed, N. Z. B. Yahaya, V. S. Asirvadam, N. Saad, R. Kannan, and O. Ibrahim, ''Development of power electronic distribution trans former based on adaptive PI controller,'' IEEE Access, vol. 6, pp. 44970–44980, 2018, doi: 10.1109/ACCESS.2018.2861420.

[20] [20] C. Yanarates and Z. Zhou, ''Design and cascade PI controller based robust model reference adaptive control of DC–DC boost converter,'' IEEE Access, vol. 10, pp. 44909–44922, 2022, doi: 10.1109/ACCESS.2022.3169591.

[21] [21] L. Martinez-Salamero, J. Calvente, R. Giral, A. Poveda and E. Fossas, "Analysis of a bidirectional coupled-inductor Cuk converter operating in sliding mode," in *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 45, no. 4, pp. 355-363, April 1998, doi: 10.1109/81.669058.

[22] [22] Abraham, Dolly Mary. "Particle swarm optimization based sliding mode controllers for electric vehicle onboard charger." *Computers & Electrical Engineering* 96 (2021): 107502.

[23] [23] Q. Tian and K. Bai, "Widen the zero-voltage-switching range and secure grid power quality for an ev charger using variable-switching-frequency single-dual-phase-shift control," in *Chinese Journal of Electrical Engineering*, vol. 4, no. 1, pp. 11-19, March 2018, doi: 10.23919/CJEE.2018.8327366.

[24] [24] L. Jorge, H. Concepcion, M. A. Arjona, M. Lesedi and C. Ambrish, "Performance Evaluation of an Active Neutral-Point-Clamped Multilevel Converter for Active Filtering in G2V-V2G and V2H Applications," in *IEEE Access*, vol. 10, pp. 41607-41621, 2022, doi: 10.1109/ACCESS.2022.3167694.