Chapter 24
Overview of Bidirectional DC–DC Converters Topologies for Electric Vehicle and Renewable Energy System

S. Saravanan, P. Pandiyan, T. Chinnadurai, Ramji Tiwari, and N. Prabaharan

24.1 Introduction

Development in electric mobility has been increasing exponentially due to advanced technologies, noiseless operation and pollution-free property. The charging and discharging of the battery management especially gets attention for extending the life span of the batteries. Significant research has been carried out for power converters in the field of power electronics. The power flow in conventional converters is in a unidirectional way, whereas in bidirectional converters, power flow occurs in both the directions, i.e., forward and reverse directions. The applications of these converters are found in renewable energy harvesting applications like solar photovoltaic arrays, wind turbines, and fuel cells and smart grids, electric vehicles, uninterrupted power supplies and aerospace applications. The bidirectional configuration-based converters act as interfacing element between energy storage devices and power sources which shrink the size of the converter and enhance the performance of the overall system because the requirement of two individual converters is not required to perform the forward and reverse directions

S. Saravanan
Department of EEE, Sri Krishna College of Technology, Coimbatore, Tamilnadu, India

P. Pandiyan
Department of EEE, KPR Institute of Engineering and Technology, Coimbatore, Tamilnadu, India

T. Chinnadurai
Department of ICE, Sri Krishna College of Technology, Coimbatore, Tamilnadu, India

R. Tiwari
Department of EEE, Sri Krishna College of Engineering and Technology, Coimbatore, Tamilnadu, India

N. Prabaharan (✉)
School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur, Tamilnadu, India

N. Priyadarshi et al. (eds.), *DC–DC Converters for Future Renewable Energy Systems*, Energy Systems in Electrical Engineering,
https://doi.org/10.1007/978-981-16-4388-0_24

of power flow. The buck or boost converter is used based on the energy storage system location, and the corresponding control strategy is employed to adjust the current or voltage according to the system requirement [1].

A bidirectional DC-to-DC converter is employed in many applications where the direction of current in both the ways depending upon the mode of operation owing to its inherent features. With the purpose of starting and accelerating the vehicle to drive in an uphill location, an additional power is required in order to boost up the high-voltage DC bus. The required higher power can be achieved through secondary batteries installed in electric vehicles in which bidirectional DC-to-DC converter that provides the maximum amount of current from the batteries during motor starting stage. In contrast to unidirectional converter configurations, it can reverse the direction of the current and power flow to be precise, and the supplementary battery present in the BOEVs takes up regenerative energy returned from the motor in deceleration condition [2].

Smart grid and PHEVs charging station uses the bidirectional DC–DC converter. In this situation, bidirectional DC–DC converter is employed to charge the electric vehicle batteries from the connected grid side and fed back to the batteries of PHEVs to the grid side subject to energy demands. For this reason, the bidirectional DC–DC converters are needed with high reliability, higher efficiency and low-cost features to utilize in the charging station.

This converter is classified into two major groups, such as non-isolated configuration and isolated configuration. The transfer of power taking place without using magnetic isolation is known as non-isolated topology. Therefore, this topology does not have a transformer and is in need of galvanic isolation features like a high step-up voltage gain which is simple in construction and of lesser weight. The non-isolated topology is the best choice when weight and size are the key factors in specific applications. As opposed to the non-isolated converter, the isolated converter topology converts DC-to-AC voltage, and it is given to the higher frequency transformer. The output of the transformer is given to the rectifier to get the DC output voltage. Generally, the voltage transfer ratio of the isolated converter configurations is higher compared to the non-isolated converter topologies [3].

The control technique employed in a bidirectional converter is based on the topology and the issues occurred in the controller part in real-time scenario. The applications which do not need isolated configuration topology, non-isolated converter topology are preferred due to low cost and simple in construction and also possible to implement without using a transformer. The isolation between sources and load is needed in case of high-power applications. As a result, an isolated converter configuration is a more suitable choice. The unique features of this isolated converter topology are electrical isolation, high reliability, simple to implement the soft-switching control technique, safe operation and equipment protection. Despite choosing the specific configuration for the bidirectional DC-to-DC converters [4], higher efficiency as well as hybrid control techniques is needed to implement these converters.

The board categories of bidirectional DC-to-DC converter topology along with control strategies are discussed in this chapter. This review is useful for the researchers pursuing the field of bidirectional converter topology in diverse applications.

24.2 Non-isolated Bidirectional DC-to-DC Converters

Non-isolated bidirectional DC-to-DC converter is generally constructed using an anti-parallel diode with the switch and including a controllable switch with diode present in the unidirectional DC-to-DC converter. This non-isolated converter is categorized into boost, buck, cuk buck–boost and so on depending upon the operation and output requirement. In addition, interleaved multilevel and switched capacitor configurations are dedicated only for voltage boosting technique. Therefore, the non-isolated bidirectional configuration-based converters are divided further into eight clusters as follows.

24.2.1 Buck and Boost Derived Converter

The basic non-isolated bidirectional buck and boost DC-to-DC converter was reported depending upon on the unique boost and buck configuration [5]. Figure 24.1 shows the bidirectional configuration which is deduced from the unidirectional buck and boost configuration. On the other hand, bidirectional boost and buck converter can be formed by substituting the bidirectional switches with unidirectional switches available in the unidirectional converter. The converter which performs the conversion operation from low voltage (LV) level to high voltage (HV) level is known as boost converter, whereas buck converter performs the operation in converse way.

24.2.2 Buck–Boost Derived Converter

The technique adopted previously is applicable for designing bidirectional buck–boost converter by replacing bidirectional switches instead of unidirectional switches present in the unidirectional buck–boost converter configuration which is illustrated in Fig. 24.2. In conventional buck–boost converter topology, the voltage level can be decreased or increased as per the requirement [6]. In case of bidirectional buck–boost DC-to-DC converter gets benefited from the unique features of providing negative voltage output and power flow in both the directions.

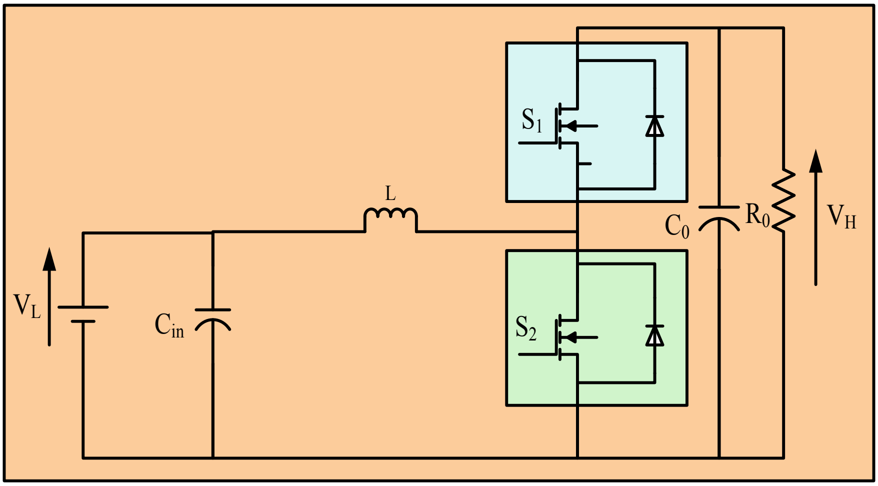

Fig. 24.1 Buck and boost derived bidirectional converter

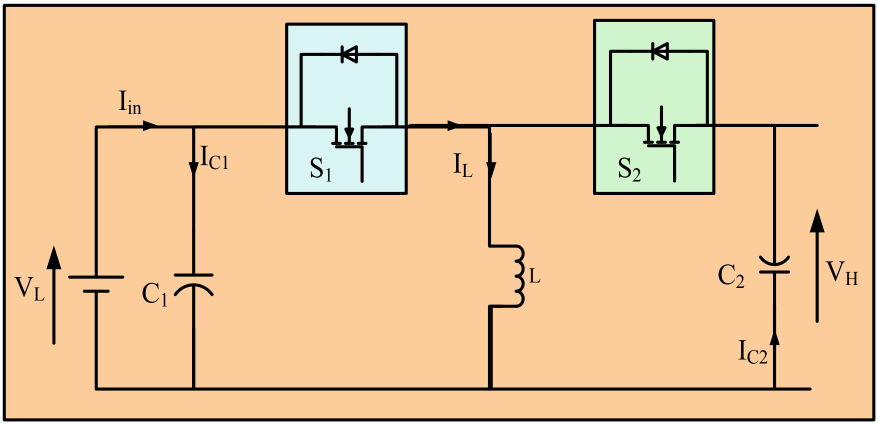

Fig. 24.2 Buck and boost derived bidirectional converter

24.2.3 Ćuk Derived Converter

Figure 24.3 illustrates the Cuk converter which has characteristics of continuous input and output current flow in both the directions by means of employing pair of bidirectional power switches in place of the diode and power switch combination of the regular circuit configuration. Some modifications have been implemented in the bidirectional non-isolated Cuk converter. In general, unidirectional Cuk converter with coupled inductor proposed to reduce the ripple content in the input and output

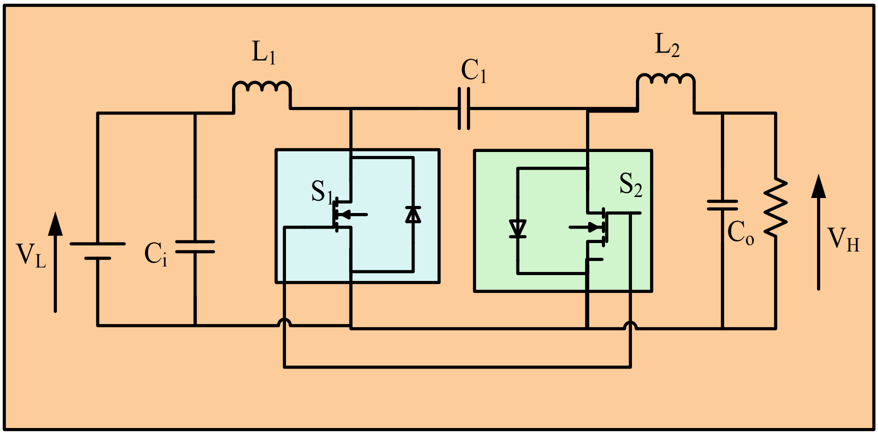

Fig. 24.3 Cuk derived bidirectional converter

current [7]. This method may be utilized to the bidirectional non-isolated Cuk converter configuration which has the potential features for advance analysis in the area of bidirectional Cuk converter with coupled inductor configuration.

24.2.4 Zeta and SEPIC Derived Converter

Zeta as well as Single-Ended Primary-Inductor (SEPIC) is the next level of DC-to-DC converter configuration that is constructed by means of reconfiguring the elements of Cuk converter topology to get positive output voltage. The SEPIC/ ZETA bidirectional converter shown in Fig. 24.4 operates like a SEPIC converter when power flow takes place form low level to high level, whereas change in power flow direction (i.e., high level to low level) occurs the same converter works as ZETA converter. The highlighted auxiliary branch in the converter design proposed in [8] provides a power delivery path to the output from the input directly and mitigates the ripples in the current waveform.

24.2.5 Cascaded Converter

To enhance the voltage boosting capability as well as current stress of the converter, more than one converter is connected in cascade fashion depending on the requirement. The fundamental cascaded non-isolated bidirectional DC-to-DC converter is depicted in Fig. 24.5 which is dedicatedly meant for Electric Vehicle application. By closely observing this converter, it is formed by cascading the couple of two buck–boost bidirectional DC-to-DC converters [9]. However, to

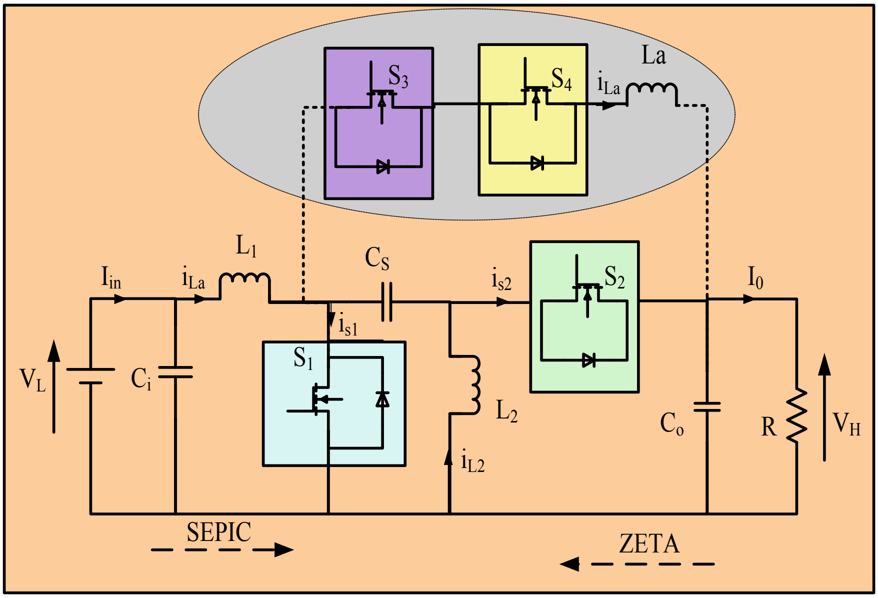

Fig. 24.4 Zeta and SEPIC derived bidirectional converter

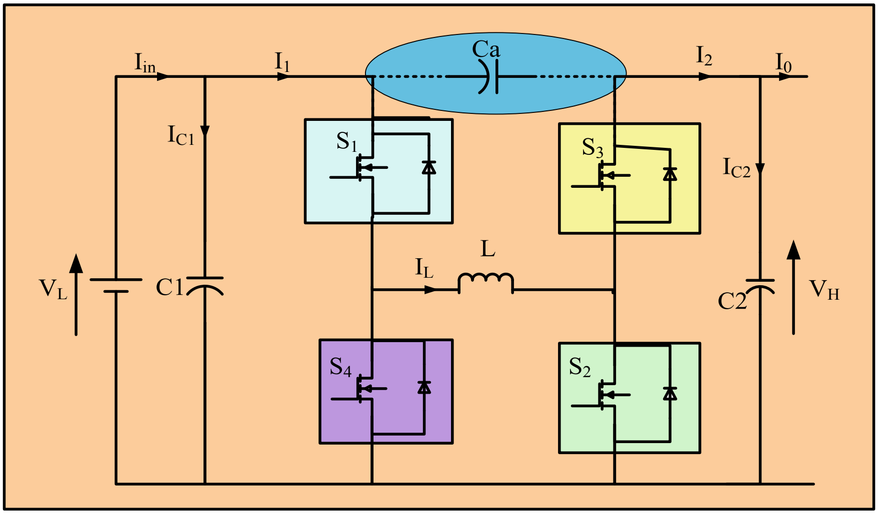

Fig. 24.5 Cascaded bidirectional converter

realize the fundamental buck–boost converter with more amount of components compared, this cascaded topology gets benefited with feature of high voltage transfer ratio along with the similar duty cycle of the switch. In addition, current stress on the switches, ripples and current stress on the capacitor, inductor and uncontrolled switches have been diminished which leads to operate this converters in higher power ratings.

24.2.6 Switched Capacitor Converter

The switched capacitor model can also be applied for improving the voltage boost capability of the converter. A bidirectional converter implemented with switched capacitor model to increase the voltage transfer ratio is depicted in Fig. 24.6. The research work presented in [10] evolved the bidirectional DC–DC converter topology implemented using unidirectional switched capacitor model. The absence of inductor in switched capacitor model gives the platform to reduce the weight in prototype design and also provides continuous current input by shunting same type of two strings realized by switched capacitor models and working together in anti-parallel manner. This can further be enlarged by incorporating the switched capacitor model.

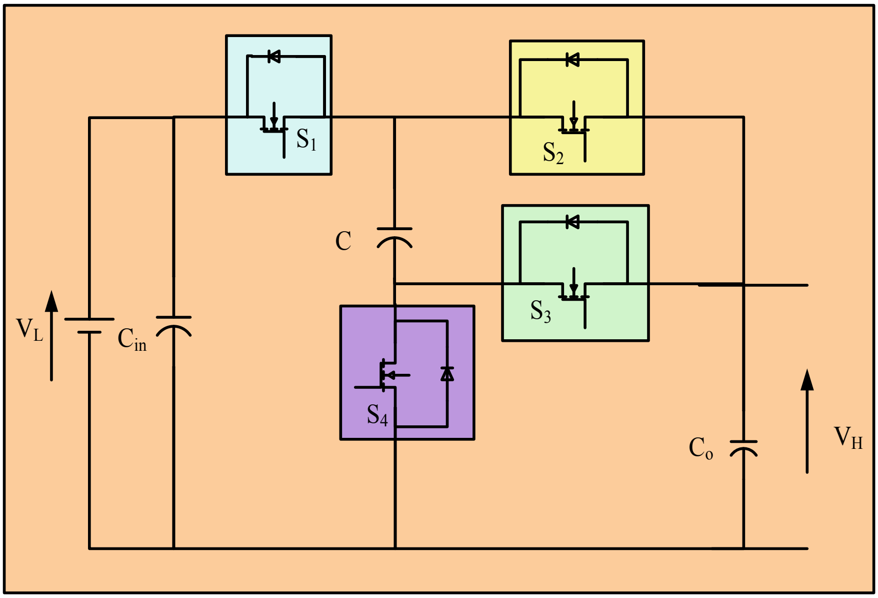

Fig. 24.6 Switched capacitor bidirectional converter

24.2.7 Interleaved Converter

The interleaved bidirectional DC-to-DC converter is depicted in Fig. 24.7 which has capability of reducing current ripple and switching frequency. Due to these advantages, it behaves as smaller electromagnetic interference filter. The research presented [11] a interleaved configuration-based bidirectional converter for automotive applications that consists of several stages which dominantly focused on filter size reduction, thermal management and better dynamic response. The interleaved converter is reported in [12] with coupled inductors in either reverse or direct manner to enhance the dynamic response of the converter and decreases the current ripple.

24.2.8 Multilevel Converter

The multilevel bidirectional DC-to-DC converter is illustrated in Fig. 24.8. A switching unit is employed at the same time as recurring pattern in every level in order to give high voltage transfer ratio. The proposed system in [13] implemented for dual-voltage automotive systems. The size and weight of this converter are significantly reduced due to the absence of the inductor.

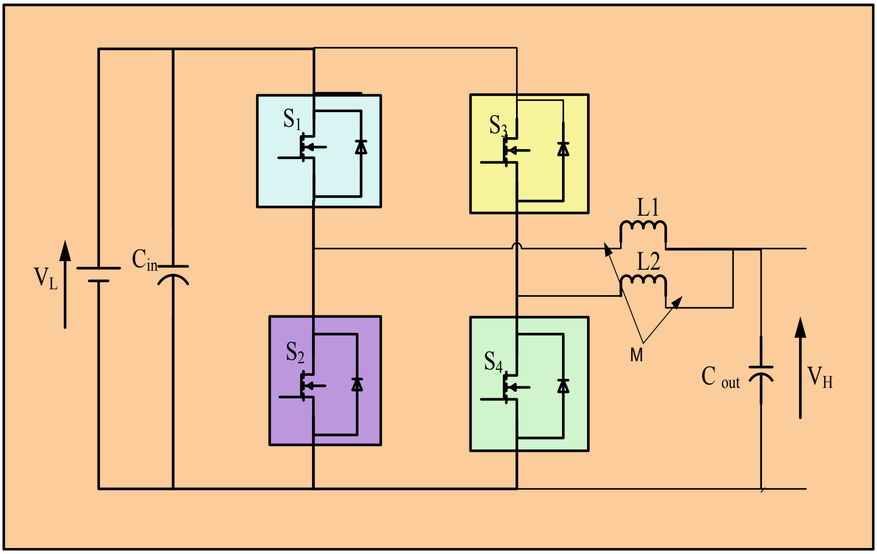

Fig. 24.7 Interleaved bidirectional converter

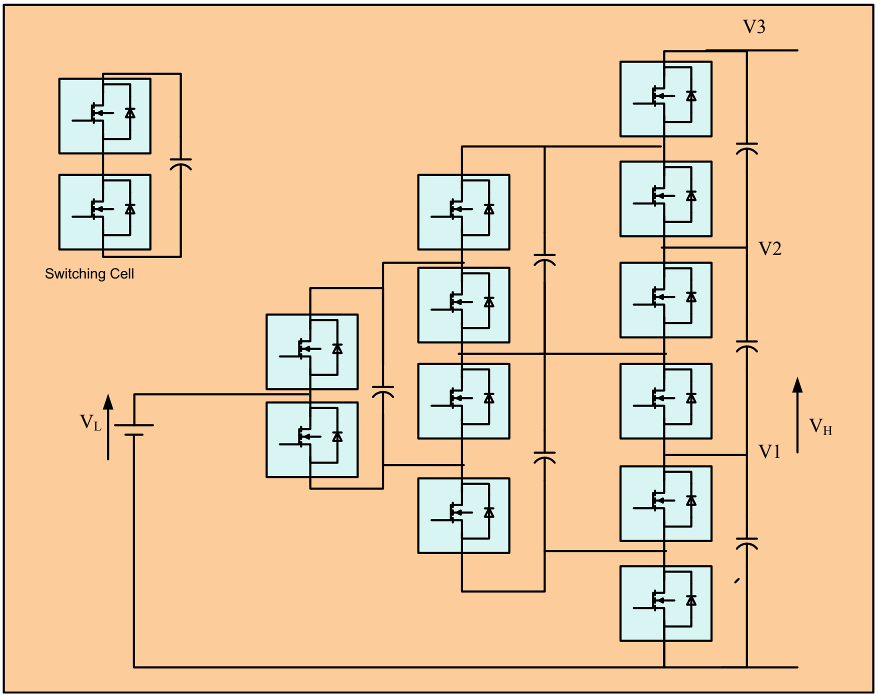

Fig. 24.8 Multilevel bidirectional converter

24.3 Isolated Bidirectional DC-to-DC Converters

Galvanic isolation is the most significant technique to establish a higher voltage gain boost capability by means of including an additional gain to the converter through the winding turns ratio in order to satisfy the output and input regulation [14]. This topology provides the prospects for realizing the multi-input and multi-output system and is also useful for the susceptible loads which are sensitive to faults as well as noisy signal. Furthermore, the safety is also considered. The isolated bidirectional DC-to-DC converter hit upon its usefulness in the area of BOEVs, PHEVs, aircraft and renewable energy resources.

24.3.1 Bidirectional Flyback Converter

The varieties of methods are available to improve the voltage boost-up capability in buck–boost converter to accomplish a higher voltage transfer ratio exclusive of isolation. On the other hand, magnetic isolation-based DC–DC converter specifically the flyback converter is constructed using transformer in place of inductor of

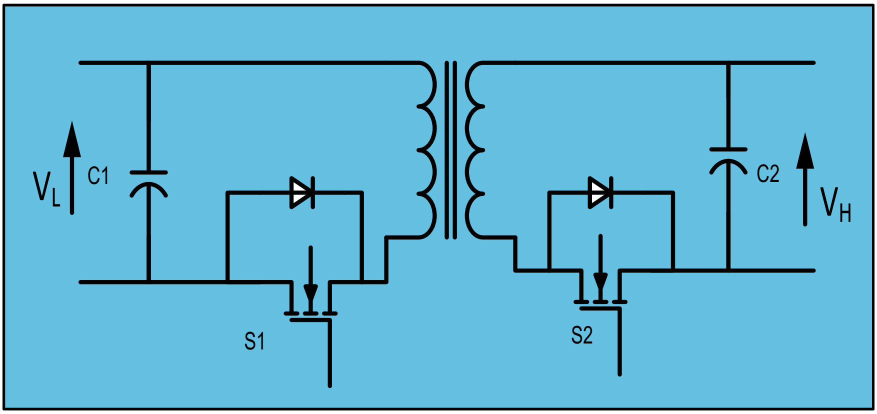

Fig. 24.9 Bidirectional flyback converter

the buck–boost DC–DC converter. A bidirectional isolated buck–boost DC–DC converter can be realized through non-isolated bidirectional converter depicted in Fig. 24.9. The forward gain of the bidirectional DC–DC converter power flow is calculated using volt-sec and charge sec balance equations which are similar to flyback converter voltage gain ratio. The design procedure for the transformer is to be considered, and snubber circuit is needed for suppressing the flyback transformer leakage current. Authors [15] proposed additional changes in this topology to increase the voltage gain.

24.3.2 Ćuk & SEPIC/Zeta Converter

By introducing the magnetic isolation in the non-isolated-based bidirectional DC–DC Cuk converter, the isolated bidirectional DC–DC Cuk converter is realized as shown in Fig. 24.10. In order to provide isolation among output and input parts with higher voltage transfer ratio which includes the transformer turns ratio and also supplies continuous input and output current [16], the coupling inductor linking the input and output directs toward the removal of ripple content in the input and output waveform which is significantly needed in renewable-based energy systems. Bidirectional SEPIC/ZETA converters were also realized in the similar way of approach.

24.3.3 Push–Pull Converter

Bidirectional push–pull converter is obtained from the unidirectional push–pull converter by incorporating the features of power flow takes place in both ways as

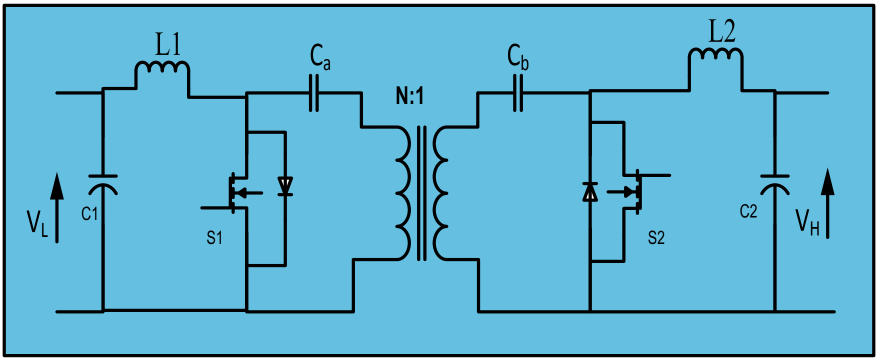

Fig. 24.10 Ćuk & SEPIC/Zeta converter

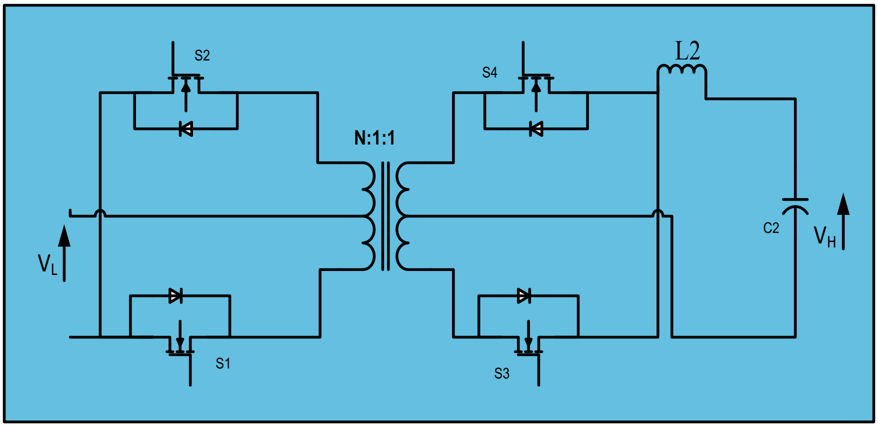

Fig. 24.11 Push–pull converter

shown in Fig. 24.11. In this converter, multiwinding transformer was used as in unidirectional push–pull converter. The authors [17] reported 3-ϕ bidirectional push–pull DC–DC converter applicable to high-power applications.

24.3.4 Forward Converter

The forward bidirectional DC–DC converter reported in [18] by considering the unidirectional forward converter is depicted in Fig. 24.12. The zero-voltage switching in this converter topology is accomplished using a clamped circuit. In addition, forward bidirectional DC–DC converter was proposed in [19] in which the leakage inductance of the transformer is utilized for creating a resonance in order to

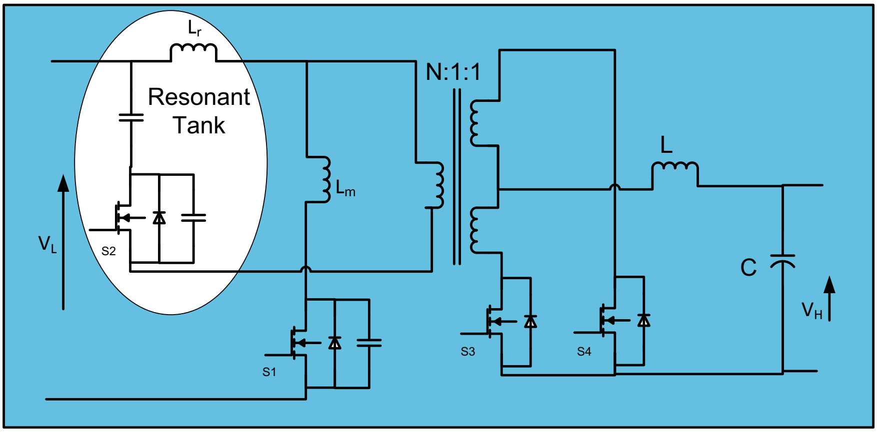

Fig. 24.12 Forward converter

realize the resonant converter topology. Hybrid converter topology has been realized in literature using the converters discussed in the isolated configuration depending upon the specific features and applications such as flyback push–pull converter, push–pull forward converter and forward-flyback converter. The transformer primary side is deduced from one of the pointed configurations, and the transformer secondary side is deduced from alternate one either voltage fed or current fed in these hybrid topologies.

24.3.5 Dual-Active Bridge (DAB) Converter

DAB converter is the well-known converter configuration that uses end-to-end bidirectional configurations which are isolated by means of a transformer with high-frequency feature. This DAB converter may be either full bridge or half bridge and voltage fed or current fed. The fundamental design for DAB converter consists of two full-bridge configurations and placed in both sides of the transformer. The number of switches employed in the converter is directly proportional to the power flow of this converter. The researcher reported [20] a work that has eight power switches with galvanic isolation which is most suitable configuration for automotive system realized with high voltage transfer ratio and also applicable for applications involving high power requirement. The control scheme employed converter gives highly efficient optimization. The basic circuit diagram of the derived DAB converter in Fig. 24.13 which consists of two stages. In the first stages, the DC–AC conversion takes place depending upon the desired specifications either a current-fed or voltage-fed full-bridge converter. A high-frequency step-up transformer amplifies the AC voltage level with galvanic isolation taken place in the second stage. A resonant circuit utilized in the converter along with the transformer

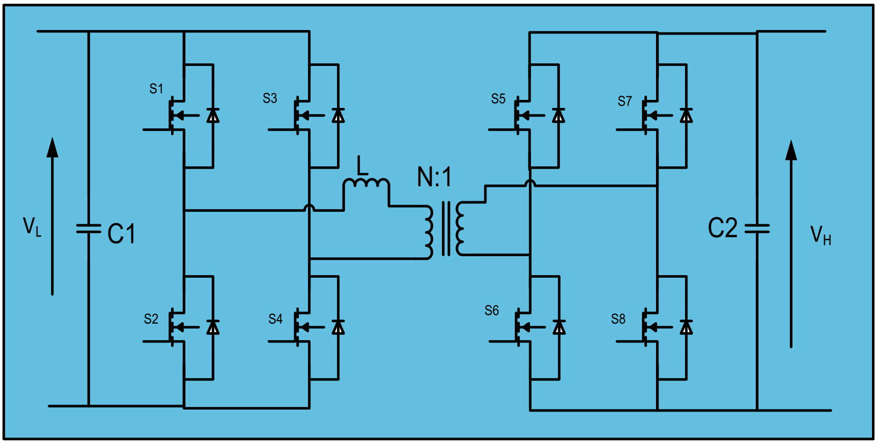

Fig. 24.13 Dual-active bridge converter

assembly helps in achieving either zero current switching or zero-voltage switching and consequently the efficiency gets improved [21]. Depending upon the specific requirement, either a current or a voltage-fed full-bridge converter does the AC-to-DC alteration in the third phase.

24.3.6 Dual Half-Bridge Converter

Half-bridge DAB consists of only four switches, and it is dedicated for low-power applications. Dual half-bridge DC-to-DC bidirectional converters along with voltage-fed configuration presented in [22] are depicted in Fig. 24.14. There is no inductor in the converter topology leads to no zeros in the right half of the s-plane. This makes the converter with minimum phase behavior and very easy to design the controller. Researchers reported the dual half-bridge bidirectional DC–DC converter which is developed with current-fed half-bridge configuration in primary side of the transformer as well as a voltage-fed half-bridge configuration in secondary side of the transformer. Another work in the dual half-bridge converter reported in [23] is exactly reverse configuration (i.e.) a voltage-fed configuration in primary side of the transformer and a current-fed configuration in the secondary side of the transformer. Current-fed configuration-based converter generates continuous current waveform which is suitable for electric vehicle applications. Authors implemented [24] interleaved bidirectional dual half-bridge configuration to enhance the voltage boost-up capability in their study to decrease the transformer ratio and current stress.

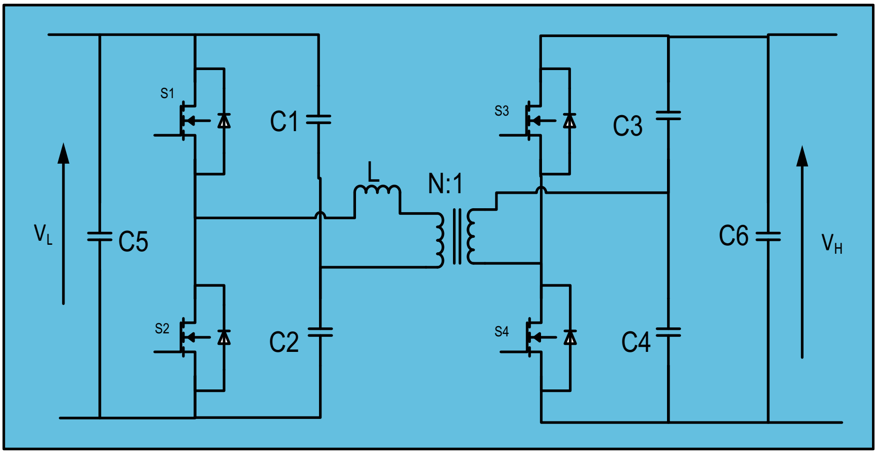

Fig. 24.14 Dual half-bridge converter

24.3.7 Half-Bridge-Full-Bridge Converter

In uninterrupted power supply (UPS) design, an isolated bidirectional converter used the voltage-fed half-bridge configuration in primary side of the transformer and voltage-fed full-bridge configuration in secondary side of the transformer shown in Fig. 24.15. This design makes converter with a smaller number of switches in comparison with DAB, and it leads to less complication in designing the controller for the same. This topology is very much preferable for combining pair of switch buck–boost converters in the half-bridge part to realize a whole UPS design. The authors [25] reported the full-bridge-half-bridge bidirectional DC–DC converter with impedance circuit which makes the system give better performance.

24.3.8 Multiport DAB Converter

The applications such as renewable energy integration system and electric vehicles require multi-input converters as reported in [26]. DAB-based isolated bidirectional multi-input bidirectional DC–DC converter implemented by means of multiwinding transformer configuration with decoupled power flow architecture is depicted in Fig. 24.16. The best usage of duty cycle as well as power flow control to maximize the system behavior is one of the significant research areas in multiport converters topology which is reported in [27].

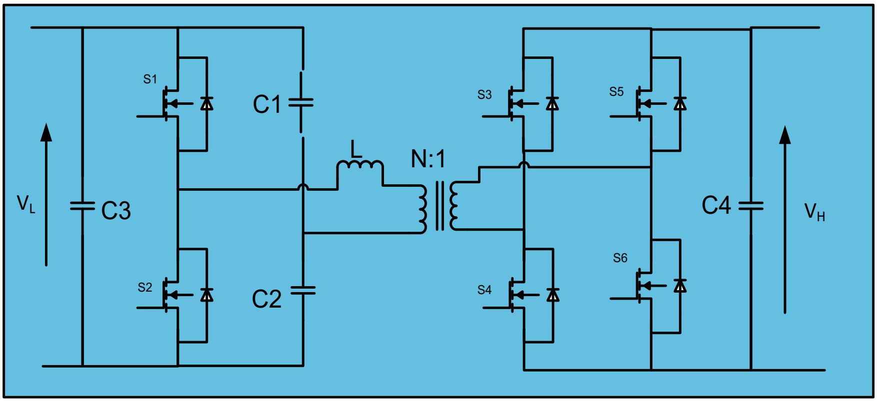

Fig. 24.15 Half-bridge-full-bridge converter

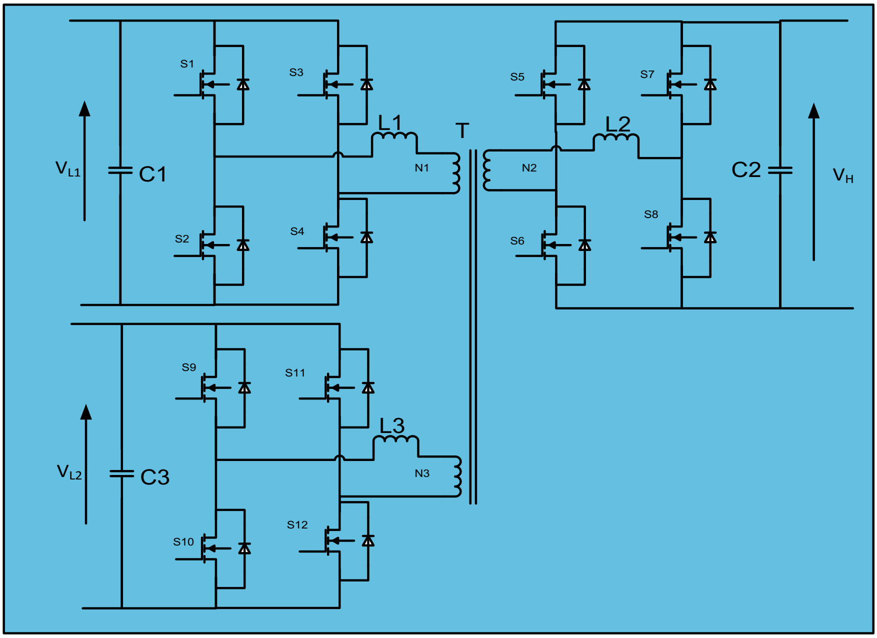

Fig. 24.16 Multiport DAB converter

24.4 Control Strategies

The selection of right control strategies for bidirectional converter configurations is based on the types and control issues arise in real-time scenario. The variety of control strategies employed in isolated and non-isolated converter configuration are discussed in the section.

24.4.1 Proportional–Integral–Derivative (PID) Control

A PID controller is a very simple controller shown in Fig. 24.17 which makes most of the researchers to select it as first choice for designing a control strategy. This PID controller is utilized in most of the converter configurations as well as variety of control problems and also used in combination along with another control strategy too. The major problem encountered in non-isolated bidirectional converter is power flow control in both directions.

Authors proposed [28] the technique in which real and reactive powers are controlled separately through controlling the real and reactive powers correspondingly; then only the real and reactive powers in AC side are controlled with the help of inverter. Further, the inverter is controlled by means of PWM and reference values. In similar way, the voltage in DC bus is controlled through a proportional integral controller and given to the power boosting circuit.

The transition stage for the bidirectional converter is generally classified into two categories. The stages are low voltage (LV) level to high voltage (HV) level and vice versa. The LV and HV are the key control input variables for the system. The traditional control schemes exploit low and high voltages for battery charging and discharging and so that this controller does not have capability to hold off the large transient at the time of transition from LV level control to HV level control. In order

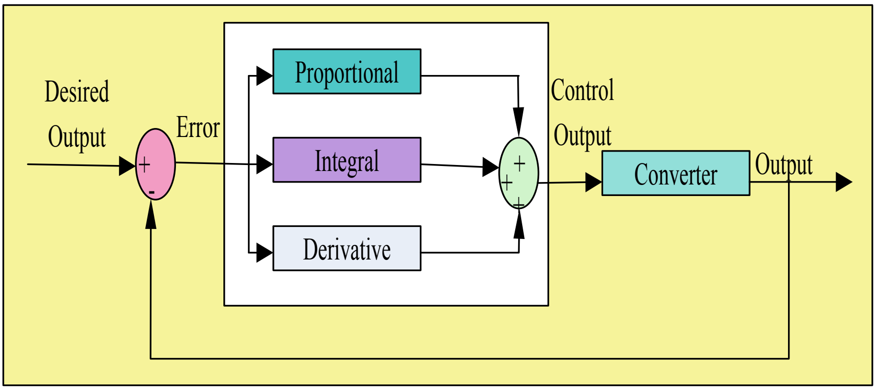

Fig. 24.17 PID controller

to reduce these problems, a PI control regulator is employed depending upon the pulse width modulation (PWM) technique which gives continuous power to the loads and diminishes the transition time as well as size of the capacitor present in the DC bus.

Multiple converter topologies provide high power efficiency with optimal integrated solution and low cost. To design a suitable control strategy for a non-isolated MIMO (Multi-input & Multi-output), multilevel bidirectional DC–DC converter is a challenging task which gives random number of voltage controllable nodes and power flow in both the directions. The job of the control strategy is to adjust the capacitor voltages of every module depending upon the specified reference values assigned for every nodal voltage. In view of that every row in the converter configuration operated along with an outside loop of PI regulator for regulating the voltage across the capacitor of the respective row path and likewise every unit of the bidirectional converter configuration operated with a higher bandwidth inside the loop of PI regulator. The inductor current is regulated by means of current controller employed in the corresponding module and set the duty cycle value for the required operation. The suitable way of inductor current regulation is used to protect the switching devices from the over current.

The procedure for stability analysis of step-down and step-up topology is similar. The local stabilization analysis performs the task by using eigenvalues of the linear system. On the other hand, the dynamics of the converter and control strategies proposed are nonlinear and to do stability analysis, the closed-loop control system ought to be linearized about the equilibrium point. The bode plot technique is used for stability analysis of transition of power flow takes place among the pair of step-down and step-up stages of the bidirectional converter. Therefore, required transfer function should be linear for analysis which can be implemented through state space averaging technique (SSA). The suitable control strategy must be designed with the help of stability analysis data obtained from bode plot.

24.4.2 Sliding Mode Control

The bidirectional converter consists of nonlinear elements which enable converter dynamic equation in nonlinear. One of the best ways to develop a control scheme dedicatedly for a nonlinear equation is that linearize the nonlinear equation about the optimum point by means of existing methods of linearization. Nevertheless, the estimation algorithm along with these techniques represents the improper system model. In linear model, the disturbance and perturbation are ignored. Hence, to achieve the desirable results as well as the system including the perturbation and disturbance existence, the controller should be designed with nonlinear strategies. Sliding Mode Controller (SMC) employed converter is illustrated in Fig. 24.18.

SMC falls under nonlinear control scheme which is more familiar for its unique features like fast, finite-time response, robust, insensitive to external perturbation

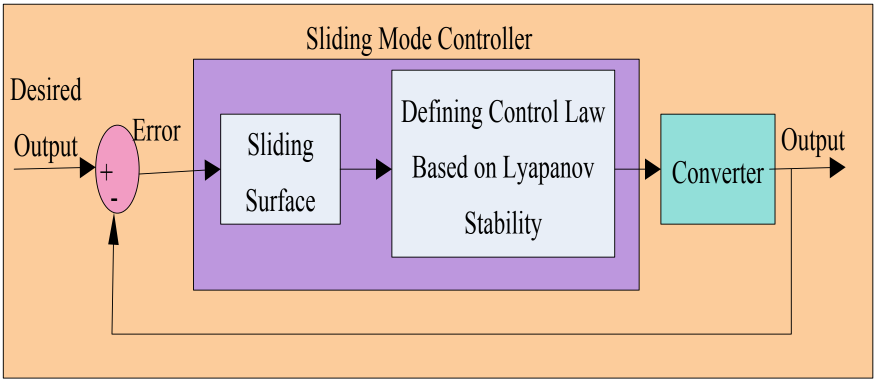

Fig. 24.18 Sliding mode controller

and parameter variation. This control strategy is applicable for both linear and nonlinear systems. The variable structure sliding mode controller to manage the bidirectional converter is employed for controlling the DC motor through rotor angular position.

Small-signal analysis depending upon the SSA model cannot forecast the regulator characteristics whenever a large signal present in the converter along with external perturbations. In order to overcome this issue, SMC is preferred due to its less sensitive to external perturbation and finite time convergence. However, this control strategy requires accurate parameter data as well as state information which makes the controller more complexity. Researchers reported [29] three variety of sliding surfaces to analyze the three particular switching states in a bidirectional DC-to-DC Cuk converter topology. This performance analysis reveals that whether the discontinuity surface is in linear grouping of the output voltage and current as well as negative magnetic coupling among the inductors; henceforth, the converter system will be less sensitive to the voltage output changes in steady-state condition.

Researchers in their work [30] proposed the applications of SMC for the bidirectional converter used in storage system for microgrid applications. The SMC is preferred due to energy resources as well as load demand fluctuations over a period of time. The SSA model based on microgrid systems is nonlinear; therefore, the equivalent load would also be nonlinear in nature. Sometimes, single control strategy is not sufficient enough to solve the problem. In that case, researchers go for hybrid versions to utilize the advantages of changing control strategy techniques. For example, the traditional method of cascade control technique uses pair of PI controllers in which outer loop controls the higher voltage side of the capacitor voltage with inner loop regulates the current flowing through inductor. In the view of such circumstances, some problems like severe variations occur in load as well as line, PID control strategy may not be the suitable for achieve the required performance. Therefore, PI controller in combination with a nonlinear fixed-frequency SMC to attain the required dynamic response and improve the system performance. In fuzzy-based sliding mode controller is developed for reproducing the energy for an ultra-capacitor in order to decrease the chattering problems occur in normal SMC. The combination of these two control strategies directs to robust controller even if the external perturbation is present and also diminishes the variations of the real-time response about the expected results.

24.4.3 Dynamic Evolution Control

In case of electric vehicle application, frequent acceleration and decelerations are required. In this view, a fastest dynamic response is the ultimate prerequisite for this type of applications. The fuel-cell-powered electric vehicle may not have tendency to offer a fastest dynamic response that is sorted out through ultra-capacitor usage as an additional power source [31]. The bidirectional converter is used to connect the ultra-capacitor to the fuel-cell-based electric vehicle. In this system, voltage drop is considerably minimized once the instant variation occurs in the load current. This type of nonlinear system prefers dynamic evolution control strategy as shown in Fig. 24.19. The fundamental idea behind this control strategy is to mitigate the dynamic steady-state error as well as forcing to chase the progress path in spite of disturbance present.

This type of control strategy and the dynamic characteristics pertaining to the control system work mainly depending upon the target equation with respect to time. The control strategy law related to this technique does not need accurate level of knowledge about the model parameters; therefore, it can balance the entire changes in the output and input voltages as well as variation in current flowing though the inductor which is an additional benefit of this control strategy which leads to produce enhanced system performance. From the obtained results, the developed controller is capable of responding to the fast-varying load conditions and returns to charge in the nominal level of voltage while power incurred due to fuel cell is larger compared to the load requirement or else vehicle is in braking mode of operation.

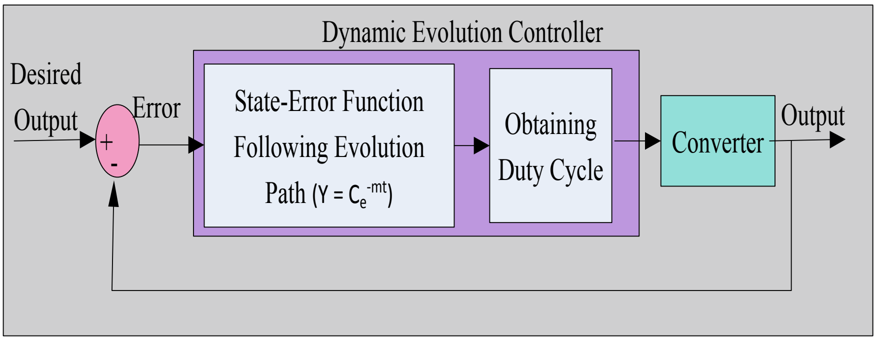

Fig. 24.19 Dynamic evolution controller

24.4.4 Model Predictive Control (MPC)

MPC strategy is derived from the predictive control scheme that utilizes the predefined function to build a system in which system parameters follow the set point values as illustrated in Fig. 24.20. This control strategy has its significant features like reference tracking characteristics, fast dynamic response and easy to implement using microprocessor. Researchers [32] proved that this control strategy is applicable for bidirectional converter used in battery-operated electric vehicles.

This control scheme requires exact discrete-time system model; then, only the forecasting and optimization stages are to be developed. In prediction block of the system, to implement the control strategy method, the measurement data is fetched from the preceding discrete-time block and the forecasted data is specified as a function of concurrent control variables in every converter switching conditions. In last, all predicted values are transferred into the optimization block. An optimization problem is solved in an online depending upon the predefined cost functions in the optimization stage and predicted values in each time step which guides to the optimal control action.

The linear-type MPC scheme needs a linear input–output equation to indicate the process flow. The main drawbacks in model predictive controller strategy are to produce good performance only when algorithm present inside the dynamic model should completely in linear or act liner according to the operational area. In order to eliminate this issue, the multi-MPC strategies were reported which employs multimodel control system to linearize the nonlinear model process of every model in local environment at various operating points. However, multiple MPC cannot be useful to carry out the nonlinear dynamic characteristics. The comprehensive dynamic control matrix utilizes the nonlinear system model to attain the accurate linear system model locally at each sampling time period. This method ensures that the linear system model to be changed in every optimization time interval to acquire

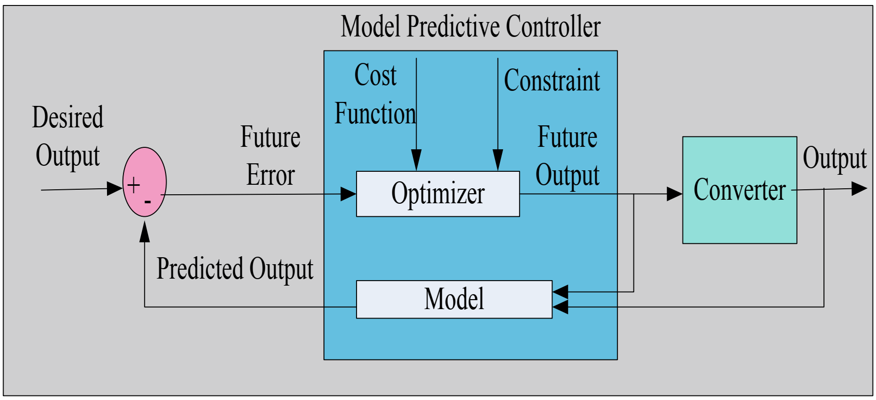

Fig. 24.20 Model predictive controller

the nonlinearity effects to be considered in every sampling step. Furthermore, the deviation occurs between nonlinear system model, and linear system model will be drastically reduced with the help of alternate algorithm. This method easily reduces the limitations caused by multiple MPC.

24.4.5 Fuzzy Logic Control (FLC)

FLC is preferred when the system is nonlinear, insensitive with parameter variation, inaccurate model, uncertainty and load disturbance. The time-variant and nonlinear behavior of converter switches creates a platform to model the single-stage converter dynamics in very tough manner. Furthermore, the charging and discharging circuits in a single-stage converter have a broad span of variation. FLC-based bidirectional converter is illustrated in Fig. 24.21.

Authors reported [33] two control strategies such as FLC and SMC for controlling the charging and discharging of battery of a DAB converter. In comparison with SMC, FLC can be implemented without enough knowledge about the system parameters, and less measurement is needed to design a controller. An artificial neural network (ANN) is an another variant of intelligent control strategy which is applicable for any systems owing to its learning behavior; therefore, it is well suited for nonlinear system. The major benefits are no need of thorough knowledge pertaining to the system, learning by training the large and complex earlier data enables to resolve the difficult problems in the easiest way. Authors implemented [34] an artificial neural network (ANN)-based controller to control the boost converter output voltage and enhance the system performance at the end of transient operating condition. The results obtained from the simulation in this control scheme

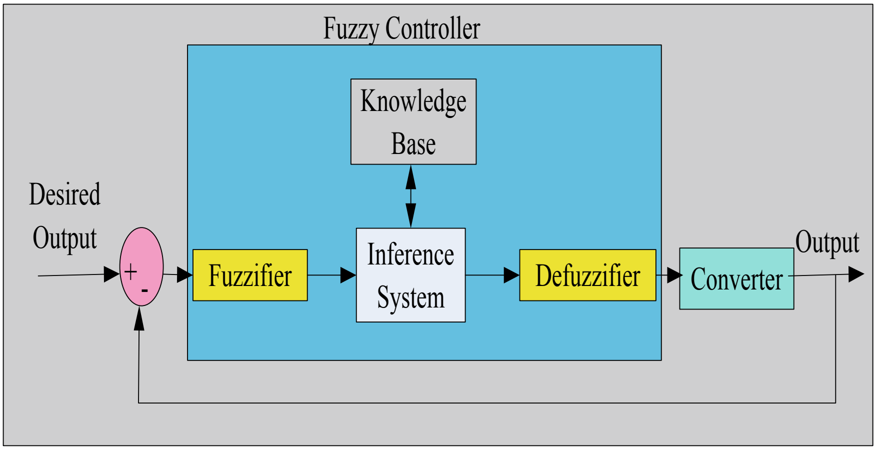

Fig. 24.21 Fuzzy logic controller

are similar to the working of a PI controller with a fastest dynamic response that reduces the overshoot.

Design of FLC requires skilled knowledge to derive the control strategy law; otherwise, it has influence on the system performance. In order to minimize the error, precise knowledge is highly appreciable. ANFIS (Adaptive-Network based Fuzzy Inference system) is employed to mitigate the expected error and adjust the controller parameters by means of gradient descent method and least square error estimation at the time of learning stage.

24.4.6 Digital Control (DC)

DC strategy-based controller produces on output which will be processed by the computer directly from the continuous-time error input signal. Once the data is processed, the discrete time signal is given to the digital controller. Then the output of the controller is sent to the bidirectional converter topology. The general block diagram of the digital control strategy is illustrated in Fig. 24.22. The digital control strategy is well-known controller scheme because of the existence of microcontrollers which process the inputs within microseconds. The authors reported [35] the bidirectional flyback converter using microcontroller. In this control scheme, the converter is utilized for mitigating the electromagnetic interference and switching loss occur in the capacitor without taking the sensor input from high-voltage side in charging/discharging phases of the load capacitance based on valley switching technique. The input voltage and VDS(LV) of the MOSFET are compared in this technique by means of high-speed comparator, and then it is given the high-speed microcontroller to identify the output coming from the comparator which charges and gives a fixed Ton (on-time) pulse which drives the specific actuator. The proposed control strategy provides fast charge/discharge speed and also higher efficiency.

In order to implement a precise small-signal model in DAB converter, the skills on modulation method are essential as well as the electromagnetic interference (EMI) filters need to be incorporated for considering their relation with respect to DAB. Nowadays, digital signal processors (DSPs) are widely used due to its high computational performance with least cost. The benefits of using digital controller are higher flexibility in comparison with analog electronics, immunity to EMI, improve the fault and process monitoring by means of external interface/network connection. Hence, a digital control strategy is utilized for controlling the DAB reported in [35], further, to obtain the transfer function in discrete time with modeling which will be utilized immediately for the design of controller. Researchers proposed the intelligent controller strategy like soft-start control and dead-band switch to modify the directions of power flow smoothly in the bidirectional converter and also keep the converter safe from the inrush current at the starting condition. This variant of controller gives a platform to control the power flow in both directions and enhance the conversion of power in efficient way in

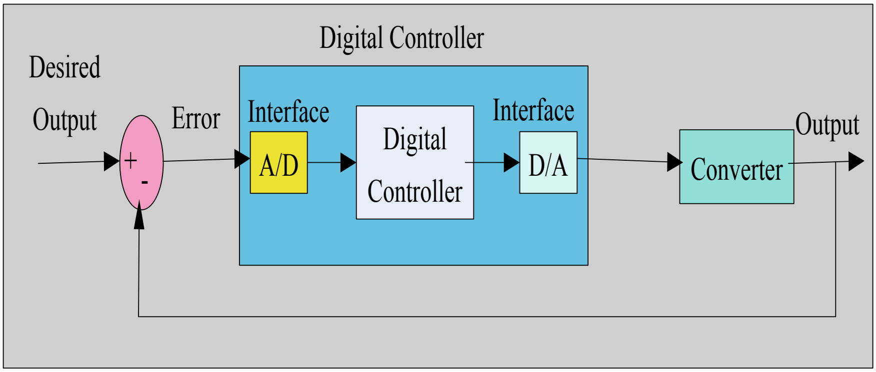

Fig. 24.22 Digital controller

low-voltage side distribution systems. This configuration can work with Zero-voltage switching in the primary side and soft commutation technique in the output rectifier side. Furthermore, this converter does not need any snubber and clamp circuits for mitigating the voltage stresses in the power semiconductor switches. The DSP processor was used for implementing all control algorithms related to commercial applications.

In addition, distribution system and power management need the integration of different load types, renewable energy resources as well as energy storage devices. The Field Programmable Gate Array (FPGA)-based DC strategy proposed in [36], in which a greater number of sources and loads are integrated by means of software reconfigurable-based power modules in connection with the DC bus. This technique gives more flexibility, enhanced reliability, simple to use with better probable energy usage by software reconfiguration done in each module. The concept of indistinguishable modules drastically diminishes the cost incurred for development as well as time and simplifies the system operation.

24.4.7 Boundary Control (DC)

A switching surface is defined depending upon the converter large-signal trajectories to intimate the control actions to the switches. The ideal switching surface has the features such as global stability, fast dynamics and better large-signal operation. In the boundary control strategy, time-varying topology-based switching converters are more preferable. Hysteresis control and SMC are the most employed boundary control method compared to other methods for the applications in power converters. These techniques give better stability and large-signal performance even though it fails to optimize effectively. A boundary control strategy in buck converters by means of second-order switching surfaces which can attain nearby optimum large-signal output and improve the velocity of the trajectory path along with the sliding switching surface.

Boundary control turns out to be more interesting because of its attempt to attain the response in very less time; ideal optimal-time control is more sensitive to parameter variations and very difficult to achieve accurate modeling. As a result, the idea of proximate optimal-time control reported to achieve nearby the optimal-time response in large-signal disturbance. Researchers reported [37] a proximate optimal-time digital control strategy depending upon the mixture of nonlinear or linear switching surface with PID controller which deems subjective load disturbances and component tolerances in reasonable way. This approach was implemented in the voltage regulation of synchronous bidirectional buck converter.

Bidirectional DC-to-DC converters are generally controlled by means of PWM signal in which switch control signals are found out depending upon the sensing the state variable and by inserting the compensators using frequency domain techniques and small-signal average models. Different types of large-signal-based techniques have been reported [38] to enhance the robustness and transient responses of converters; however, SMC strategy is the best method to characterize both large- and small-signal system conditions as well as provide robust output responses against disturbances and uncertainties. In addition, ripple specifications and transient performance can be modified easily and, in some applications voltage, and current overshoots may be removed.

24.5 Conclusion

This study gives the overview about bidirectional DC-to-DC converters starting from the topological arrangement as well as discussed in detail about the control strategy. The bidirectional DC–DC converters are basically non-isolated configuration in which unidirectional switches are replaced with the bidirectional switches in the fundamental converter. The different types of techniques are employed to obtain the objectives like enhancing the voltage boost capability of the converter by incorporating the multicell configurations and also utilizing advanced power semiconductor materials like GaN. In addition, the control strategies and switching schemes are also investigated for non-isolated and isolated configurations of bidirectional DC-to-DC converters.

References

1. Forouzesh, M., Siwakoti, Y.P., Gorji, S.A., Blaabjerg, F., Lehman, B.: Step-up DC–DC converters: a comprehensive review of voltage-boosting techniques, topologies, and applications. IEEE Trans. Power Electron., **32**(12), 9143–9178 (2017)
2. Tytelmaier, K., Husev, O., Veligorskyi, O., Yershov, R.: A review of non-isolated bidirectional dc-dc converters for energy storage systems. In: Proceeding II International Young Scientists Forum on Applied Physics and Engineering (YSF) - IEEE, pp. 22–28 (2016)

3. Chakraborty, S., Vu, H.N., Hasan, M.M., Tran, D.D., Baghdadi, M.E., Hegazy, O.: DC-DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: State of the art and future trends. Energies **12**(8), 1569 (2019)
4. Gorji, S.A., Sahebi, H.G., Ektesabi, M., Rad, A.B.: Topologies and control schemes of bidirectional DC–DC power converters: an overview. IEEE Access **7**, 117997–118019 (2019).
5. Matsuo, H., Kurokawa, F.: New solar cell power supply system using a boost type bidirectional dc-dc converter. IEEE Trans. Ind. Electron., **1**, 51–55 (1984)
6. Caricchi, F., Crescimbini, F., Noia, G., Pirolo, D.: Experimental study of a bidirectional DC-DC converter for the DC link voltage control and the regenerative braking in PM motor drives devoted to electrical vehicles. In: Proceeding of IEEE Applied Power Electronics Conference and Exposition-ASPEC'94, pp. 381–386 (1994)
7. Majo, J., Martinez, L., Poveda, A., de Vicuna, L.G., Guinjoan, F., Sanchez, A.F., Marpinard, J.C.: Large-signal feedback control of a bidirectional coupled-inductor Cuk converter. IEEE Trans. Ind. Electron. **39**(5), 429-436 (1992)
8. Song, M.S., Son, Y.D., Lee, K.H.: Non-isolated bidirectional soft-switching SEPIC/ZETA converter with reduced ripple currents. J. Power Electron. **14**(4), 649–660 (2014)
9. Lee, H.S., Yun, J.J.: High-efficiency bidirectional buck–boost converter for photovoltaic and energy storage systems in a smart grid. IEEE Trans. Power Electron. **34**(5), 4316–4328 (2018)
10. Chung, H.S., Chow, W.C., Hui, S.Y.R., Lee, S.T.: Development of a switched-capacitor DC-DC converter with bidirectional power flow. IEEE Trans. Circuits and Sys. I: Funda. Theory and App., **47**(9), 1383–1389 (2000)
11. Garcia, O., Zumel, P., De Castro, A., and Cobos, A.: Automotive DC-DC bidirectional converter made with many interleaved buck stages. IEEE Trans. Power Electron., **21**(3), 578–586,(2006)
12. Huang, X., Lee, F.C., Li, Q., Du, W.: High-frequency high-efficiency GaN-based interleaved CRM bidirectional buck/boost converter with inverse coupled inductor. IEEE Trans. Power Electron., 31(6), 4343–4352 (2015)
13. Peng, F.Z., Zhang, F., Qian, Z.: A magnetic-less DC-DC converter for dual voltage automotive systems. In: Conference record of the 2002 IEEE Industry applications conference. 37th IAS Annual Meeting (Cat. No. 02CH37344), vol. 2, pp. 1303–1310 (2002)
14. Gorji, S.A., Ektesabi, M., Zheng, J.: Isolated switched-boost push–pull DC–DC converter for step-up applications. Electron. Lett. **53**(3), 177–179 (2017)
15. Delshad, M., Farzanehfard, H.: A new isolated bidirectional buck-boost PWM converter. In: Proceeding 1st Power Electronic & Drive Systems & Technologies Conference (PEDSTC) - IEEE, pp. 41–45 (2010)
16. Ruseler, A., Barbi, I.: Isolated Zeta-SEPIC bidirectional dc-dc converter with active-clamping. In: Proceeding Brazilian Power Electronics Conference - IEEE, pp. 123–128 (2013)
17. Kwon, M., Park, J., Choi, S.: A bidirectional three-phase push–pull converter with dual asymmetrical PWM method. IEEE Trans. Power Electron., **31**(3), 1887–1895 (2015)
18. Lin, B.R., Chen, J.J., Lee, Y.E., Chiang, H.K.: Analysis and implementation of a bidirectional ZVS Dc–Dc converter with active clamp. In: Proceeding 3rd IEEE Conference on Industrial Electronics and Applications, pp. 382–387 (2008)
19. Khodabakhshian, M., Adib, E., Farzanehfard, H.: Forward-type resonant bidirectional DC–DC converter. IET Power Electron., **9**(8), 1753–1760 (2016)
20. Zhao, B., Song, Q., Liu, W., Sun, Y.: Overview of dual-active-bridge isolated bidirectional DC–DC converter for high-frequency-link power-conversion system. IEEE Trans. Power Electron. **29**(8), 4091–4106 (2013)
21. Jung, J.H., Kim, H.S., Ryu, M.H., Baek, J.W.: Design methodology of bidirectional CLLC resonant converter for high-frequency isolation of DC distribution systems. IEEE Trans. Power Electron. **28**(4), 1741–1755 (2012)

22. He, P., Khaligh, A.: Comprehensive analyses and comparison of 1 kW isolated DC–DC converters for bidirectional EV charging systems. IEEE Trans. Transp. Electr. **3**(1), 147–156 (2016)
23. Li, H., Peng, F.Z., Lawler, J.S.: A natural ZVS medium-power bidirectional DC–DC converter with minimum number of devices. IEEE Trans. Ind. App., **39**(2), 525–535 (2003)
24. Park, S., Song, Y.: An interleaved half-bridge bidirectional DC–DC converter for energy storage system applications. In: Proceeding 8th International Conference on Power Electronics-ECCE Asia - IEEE, pp. 2029–2034 (2011)
25. Chub, A., Vinnikov, D., Kosenko, R., Liivik, E., Galkin, I.: Bidirectional DC–DC converter for modular residential battery energy storage systems. IEEE Trans. Ind. Electron. **67**(3), 1944–1955 (2019)
26. Gorji, S.A., Ektesabi, M., Zheng, J.: Double-input boost/Y-source DC–DC converter for renewable energy sources. In: Proceeding IEEE 2nd Annual Southern Power Electronics Conference (SPEC), pp. 1–6 (2016)
27. Zhao, C., Round, S.D., Kolar, J.W.: An isolated three-port bidirectional DC–DC converter with decoupled power flow management. IEEE Trans. Power Electron. **23**(5), 2443–2453 (2008)
28. Cornea, O., Andreescu, G.D., Muntean, N., Hulea, D.: Bidirectional power flow control in a DC microgrid through a switched-capacitor cell hybrid DC–DC converter. IEEE Trans. Ind. Electron., **64**(4), 3012–3022 (2016)
29. Cao, J., Chen, Q., Zhang, L., Quan, S.: Sliding mode control of bidirectional DC/DC converter. In: Proceeding 33rd Youth Academic Annual Conference of Chinese Association of Automation (YAC) - IEEE, pp. 717–721 (2018)
30. Agarwal, A., Deekshitha, K., Singh, S., Fulwani, D.: Sliding mode control of a bidirectional DC/DC converter with constant power load. In: Proceeding IEEE First International Conference on DC Microgrids (ICDCM), pp. 287–292 (2015)
31 Samosir, A.S., Yatim, A.H.M.: Implementation of dynamic evolution control of bidirectional DC–DC converter for interfacing ultracapacitor energy storage to fuel-cell system. IEEE Trans. Ind. Electron. **57**(10), 3468–3473 (2010)
32. Pirooz, A., Noroozian, R.: Model predictive control of classic bidirectional DC–DC converter for battery applications. In: Proceeding 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC) – IEEE, pp. 517–522 (2016)
33. Talbi, S., Mabwe, A.M., El Hajjaji, A.: Control of a bidirectional dual active bridge converter for charge and discharge of a Li-Ion Battery. In: Proceeding IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society, p. 000849–000856 (2015)
34. Dhivya, B.S., Krishnan, V., Ramaprabha, R.: Neural network controller for boost converter. In: Proceeding International Conference on Circuits, Power and Computing Technologies (ICCPCT) – IEEE, pp. 246–251 (2013)
35. Krismer, F., Kolar, J.W.: Accurate small-signal model for the digital control of an automotive bidirectional dual active bridge. IEEE Trans. Power Electron, **24**(12), 2756–2768 (2009)
36. Rodriguez, M., Stahl, G., Corradini, L., Maksimovic, D.: Smart DC power management system based on software-configurable power modules. IEEE Trans. Power Electron. **28**(4), 1571–1586 (2012)
37. Yousefzadeh, V., Babazadeh, A., Ramachandran, B., Alarcón, E., Pao, L., Maksimovic, D.: Proximate time-optimal digital control for synchronous buck DC–DC converters. IEEE Trans. Power Electron., **23**(4), 2018–2026 (2008)
38. Galvez, J.M., Ordonez, M., Luchino, F., Quaicoe, J.E.: Improvements in boundary control of boost converters using the natural switching surface. IEEE Trans. Power Electron., **26**(11), 3367–3376 (2011)