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Advanced DC-DC Converter Topologies and ANFIS-Based Control for Efficient EV Battery Charging: A Comprehensive Review

Ashutosh Soni[1] Rahul Singh[2]
[1]M. Tech Scholar, Department of Electrical &Electronics Engg. OCT Bhopal (India)
[2]Assistant Professor, Department of Electrical & Electronics Engg. OCT Bhopal (India)

Abstract

The increasing adoption of Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs) has created a growing demand for efficient, reliable, and high-performance battery charging systems. This review focuses on advanced DC-DC converter topologies and control strategies for EV battery chargers, emphasizing power factor correction (PFC) and wide voltage adaptability. The paper explores the limitations of conventional buck-boost converters and highlights the advantages of interleaved boost cascaded-by-buck converters in terms of reduced ripple, improved efficiency, and power quality. Recent advancements in intelligent control techniques, particularly Adaptive Neuro-Fuzzy Inference System (ANFIS), are discussed and compared with traditional PI controllers. Simulation studies demonstrate that ANFIS offers superior voltage regulation and lower total harmonic distortion (THD), making it a promising control solution for next-generation EV chargers. The review consolidates current research trends and identifies future opportunities in charger design for sustainable electric transportation.

Keywords: Electric Vehicle; Conventional Buck-Boost Converter; PFC Converter; MATLAB Software; PI and ANFIS Fuzzy Controller.

1.INTRODUCTION

There has been a gradual but steady infiltration into mainstream transportation of electric cars because of electric vehicles' enormous beneficial influence on the environment. However, despite the fact that a lot of EVs are being produced, the number of EVs on the road is rather low. Lithium-ion batteries are the most often used sort of EV battery. Despite the fact that electric and plug-in hybrid cars are the most fuel efficient, they have not been extensively embraced. Batteries, pricing, and charging issues have all been cited as significant reasons for not implementing these cars on the grid. Another issue with PHEVs as compared to traditional fuel stations is the absence of suitable and appropriate charging infrastructure and regulatory support for energy storage solutions.

Hybrid cars employ lithium-ion batteries that are quicker and less efficient than those used in typical electric vehicles. In addition to battery life, plug-in electric and hybrid cars have a slew of additional drawbacks as compared to pure electric vehicles. For example, the HEV's fuel economy is much lower than that of an EV. Bi-directional AC-DC converters and DC-DC converters of the same origin are the most widely utilised power converters for these vehicles.[1]

Because PEVs are a relatively new technology, there aren't many charging stations around. In addition, PEV's bidirectional converters don't employ conventional architecture; instead, they're often unidirectional bridge rectifiers. As a result of the facts acquired, it can be concluded that EVs are more efficient than HEVs or PHEVs in nature due to their zero emissions, high efficiency, reduced noise, safety, and smooth operation, as well as their independence from petroleum fuel. During braking, the electric motor acts like a generator and recharges the battery as the kinetic energy is completely transformed to potential energy. This is the primary benefit of EVs. [2]

General configuration of an EV charging system

The fundamental DC of the AC power converters is used to create the EV battery chargers, which must be very powerful and effective. Unregulated or regulated rectifiers are used in AC-DC converters that use Buck / Boost or switch mode technology. In most cases, DC-AC converters are built around single-phase H-bridge inverters or three-phase inverters.

Figure Error! No text of specified style in document. General topology of EV charging panel

There are many different ways to charge an electric vehicle, and this diagram displays the most common setup. Figure 1.1 depicts the many types of power converters that may be utilised to achieve the various effects shown (numbered from number 1 to number 6). EV batteries may be recharged with either an onboard or an offboard charger (levels 1, 2, and 3). EV battery chargers may be integrated into a vehicle, either as an on-board charger or an isolated outboard charger. The EV batteries and the grid may have a one-way or two-way power flow.Modern commercial on-board chargers use unidirectional power flow because it is simple and reliable in both topology and function. Electric vehicle batteries may be used to generate electricity by controlling bidirectional charges. It's possible to think of an EV battery as a highly efficient distributed power source that may be used in a variety of ways. AC-DC converters and DC-DC converters are featured in all on/off board loaders, as seen in Figure 1.1. Nevertheless, the topologies and power ratings of the converters differ entirely within each category of chargers. [3]

PHEV

Overconsumption of fuels, depletion of these resources, a decrease in greenhouse gas emissions and a rise in oil costs have led to the emergence of the plug-in hybrid HEV (PHEV) alternative in recent years. It is only necessary to add more battery capacity, connect to an electrical outlet for charging, and alter the power electronics of a PHEV in order to make it a hybrid. As PHEVs can already travel 30-60 miles on electricity alone, they have the potential to become a new energy storage resource for the grid. [4]

Charge-depletion strategy is used in a PHEV, where the car's batteries are constantly used to enhance fuel economy, and the level of charge is generally as low as 30%. While the automobile is not in use, it will be linked to the power grid in order to deliver energy to the batteries and/or assist the grid in the event of a power failure. The plug-in car more than doubles the typical home load while it is charging. Because PHEVs may be plugged in at any point in the distribution network, the influence on the grid is a big worry. The PHEV will always be near to the energy demand, and the efficiency of stored energy in the EV's batteries is theoretically substantially better than the energy stored in hydrogen and in fuel cells hydrogen vehicles. To add insult to injury, hydrogen cars have a limited potential to provide the grid with additional services, as opposed to electric vehicles.[5]

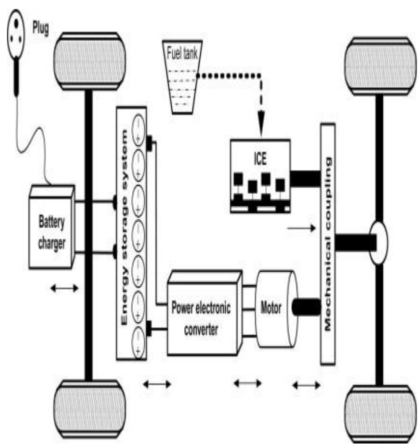

Figure 2 basic diagram of PHEV

PHEV benefits

A. Electric Utility Benefits

Peak shaving may be achieved by using the battery energy to meet a part of the feeder's local demand. In addition to lowering transmission congestion, line losses, and delays in transmission investments, peak shaving may also decrease the power system's stress level. Companies that serve customers in a deregulated market use long-term contracts with power producers and short-term spot markets to buy electricity.

Price spikes occur when power demand is at its maximum, often known as "peak loads." The use of PHEV fleet peak shaving applications helps keep the cost of power down when demand is at its highest. This savings on power may be put to good use by creating incentive schemes to encourage people to buy PHEVs and put them to work in grid-supporting scenarios. When off-peak times are available, off-peak load levelling may be achieved by using PHEVs.

DC-DC Converter

To connect the FC, battery, or supercapacitors module to the DC-link, at least one DC/DC converter is required, as can be seen from the various EV power supply configurations. Power converters in electrical engineering, referred known as DC to DC converters, are used to convert direct current (DC) from one voltage level to another by temporarily holding the input power and then releasing that power at another voltage.

Either magnetic or electric field-based storage components (inductors and transformers) may be used (capacitors). Only one direction of power may be transferred by DC/DC converters, and that is from the input to the output. In reality, bi-directional DC/DC converters are possible with almost any topology. When regenerative braking is required, a bi-directional converter comes in handy since it can flow power in either way. [6]

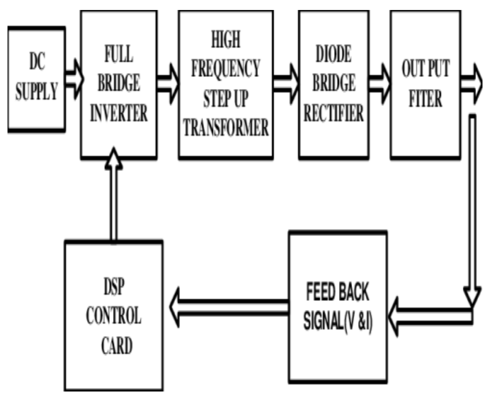

Figure 1 Basic diagram of DC-DC Converter

It is possible to regulate the input/output power flow by varying the duty cycle (the switch's on/off time ratio). Typically, this is done to regulate the output voltage, the input current, the output current, or to maintain a steady power. Isolation between the input and output may be achieved using transformer-based converters.

In addition to complexity, electrical noise, and expensive topologies, switching converters have a number of downsides. Proposals for DC/DC power converters abound in academic literature. The following are the main types of DC/DC converters:

Conventional Buck-Boost Converter

Bidirectional DC-DC converters (BDC) have recently received a lot of attention due to the increasing need to systems with the capability of bidirectional energy transfer between two DC buses. Basic DC-DC converters such as buck and boost converters (and their derivatives) do not have bidirectional power flow capability. This limitation is due to the presence of diodes in their structure which prevents reverse current flow. In general, a unidirectional DC-DC converter can be turned into a bidirectional converter by replacing the diodes with a controllable switch in its structure.

Figure shows the structure of elementary buck and boost converters and how they can be transformed into bidirectional converters by replacing the diodes in their structure. It is noteworthy that the resulted converter has the same structure in both cases. [10]

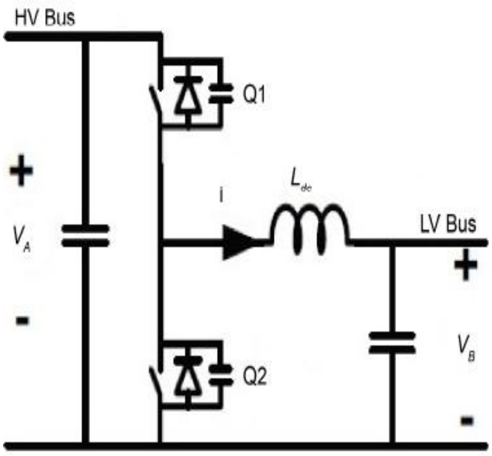

Figure 4 Bi-directional buck boost converter circuit

Mode 1 (Boost Mode): In this mode switch Q2 and diode D1 enters into conduction depending on the duty cycle whereas the switch Q1 and diode D2 are off all the time. This mode can further be divided into two interval depending on the conduction on the switch Q1 and diode D2 as shown in the Figure.

Interval 1 (Q2-on, D2-off; Q1-off, D2-off): In this mode Q2 is on and hence can be considered to be short circuited, therefore the lower voltage charges the inductor and the inductor current goes on increasing till not the gate pulse is removed from the Q2. Also since the diode D1 is reversed biased in this mode and the switch Q1 is off, no current flows through the switch Q1.

Interval 2 (Q1-off, D1-off; Q2-off, D2-on): In this mode Q2 and Q1 both are off and hence can be considered to be opened circuited. Now, since the current owing through the inductor cannot change instantaneously, the polarity of the voltage across it reverses and hence it starts acting in series with the input voltage. Therefore, the diode D1 is forward biased and hence the inductor current charges the output capacitor C2 to a higher voltage. Therefore, the output voltage boosts up. [11]

Neglecting the voltage drops across the diode and the transistor:

Voltage across HV BUS, $V_H = \frac{V_L}{(1-D)}$

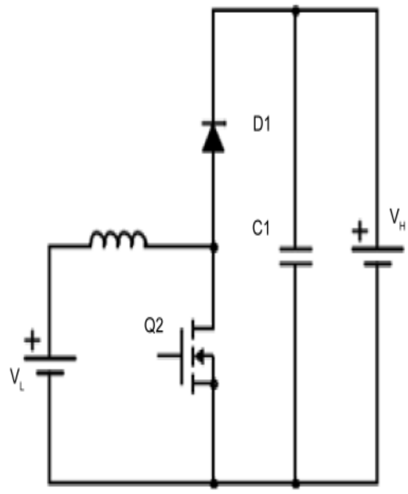

Figure 5 Boost mode operation

Mode 2 (Buck Mode): In this mode switch Q1 and diode D2 enters into conduction depending on the duty cycle whereas the switch Q2 and diode D1 are off all the time. This mode can further be divided into two intervals depending on the conduction on the switch Q2 and diode D1 as shown in the Figure 1.5.

Interval 1 (Q2-on, D2-off; Q1-off, D2-Off): In this mode Q1 is on and Q2 is off and hence the equivalent circuit. The higher voltage battery will charge the inductor and the output capacitor will get charged by it.

Interval 2 (Q1-off, D1-off; Q2-off, D2-on): In this mode Q2 and Q1 both are off. Again since the inductor current cannot change instantaneously, it gets discharged through the freewheeling diode D2. The voltage across the load is stepped down as compared to the input voltage.

Neglecting the voltage drops across the diode and the transistor:

Voltage across LV BUS, $V_L = V_H$ D

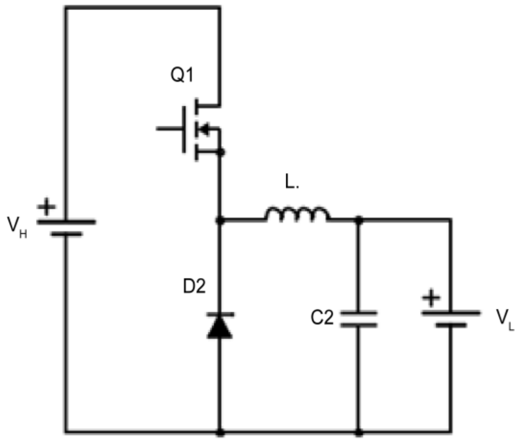

Figure 6 Buck mode operation

II. OBJECTIVES

The primary objectives of this review paper are as follows:

1.To analyze the limitations of conventional DC-DC converter topologies (buck, boost, buck-boost, SEPIC, CUK) used in electric vehicle (EV) battery charging applications.

2.To explore the design and performance benefits of an interleaved boost cascaded-by-buck converter in terms of voltage range flexibility, efficiency, and reduced ripple.

3.To evaluate the effectiveness of intelligent control strategies—specifically the Adaptive Neuro-Fuzzy Inference System (ANFIS)—in comparison to conventional PI controllers for regulating output voltage and improving power factor.

III. LITERATURE REVIEW

(Sanguesa et al., 2021) [1] As the cost of electric vehicles (EVs) decreases and people become more conscious of the effects they have on the environment and the climate, EV sales are on the rise. Battery technology, charging techniques, and research difficulties and potential for EVs are discussed in this study.. It is precisely determined how the global EV market is now doing and what the future holds for it. For starters, the battery is one of the most important components of EVs, hence a comprehensive discussion of the various battery technologies is included in the study. The numerous standards for charging EVs, as well as power control and battery energy management approaches, are also examined. Additionally, Finally, we provide our view for the near future of this sector, as well as the research areas that are still available for both business and academic groups to investigate.

(G. N. Kumar et al., 2021) [2] The fuzzy logic controller technique for an integrated PV electrical vehicle charger is used in this study to investigate a novel output from the "Bridge Less (BL) Cuk Converter (battery)." To charge the battery as cheaply as possible, this method relies on the fewest possible switch numbers. Although the EV-charger is operating under, at, or over its rated capacity, the voltage and current inputs remain stable. In addition, even with an uneven input supply, it retains steady battery properties. A robust BL-Cuk converter with fuzzy control is used. Because of the decreased switching needed by the new technology, there is no need for a DC condenser. Therefore, the condenser generates a balancing voltage above standard EV charging methods.

(Jati, 2021) [3] As the number of nonlinear loads grows, so does interest in creating power factor correction technologies. Nonlinear loads generate poor power factor and the emergence of harmonic currents, which may influence load system performance. A power factor corrector converter with a simple design and dependable performance is required, however. Because of these benefits, the "Interleaved Boost Converter" is often used as a power factor converter. With a fuzzy controller, a near-unity power factor can be achieved. Inductor design in the "Discontinuous Conduction Mode (DCM) approach" is very efficient. Simulation and hardware implementation of the suggested solution yielded considerable improvements in power factor.

(Singh et al., 2021) [4] As a beginner in the subject of power electronics, this work aims to give a critical assessment of single-phase non-isolated bridgeless power factor converter topologies. There are fewer switching devices in the converter's current route because of its bridgeless design. The inherent advantages of no isolated topologies, such as lower cost, weight, and size, as well as higher efficiency, are taken into account in this review because systems such as on-board electric vehicle battery chargers, dc power supplies, and variable speed drives all benefit from these advantages. Boost, buck, and buck/boost converters are the ancestors of these topologies. Depending on the application, the topologies may be used in either continuous or discontinuous conduction modes. The benefits and drawbacks of each topology are discussed in detail. In addition, each group (boost, buck, and buck/boost) is compared in comparative research.

(Corradini et al., 2020) [5] An unusual set of problems confronts the designer when studying power converters that operate at much higher switching frequencies than is usually the case. The formulation and assessment of conversion topologies for high-frequency power conversion, as well as associated control and modelling methodologies and design procedures, represent crucial features that are intimately linked. In the context of high-frequency converter design, characterization and assessment procedures for active and passive components intended for high-frequency operation are also critical.

(Kalyanasundaram et al., 2020) [6] There has been an enormous shift in recent decades in the production and use of electric power. The rise of the electric power business and the transportation sector are at the heart of this transition. This shift is a significant contributor to pollution of the environment and the rise in global temperatures. As a result, governments throughout the world are actively searching for alternative energy sources in order to reduce their dependence on traditional fuels and greenhouse gas emissions. Building a more sustainable society will benefit from the development of clean and renewable energy sources. Energy use in transportation is shifting from fossil fuel to electricity-based fuel at the same time. Environmental pollution and global warming are challenges that may be addressed by implementing an electric transportation system. Two-stage charging models are used to attain high efficiency in this paper's EV battery charger. By using MATLAB simulation, the design is compared to the current model. Using simulations, it can be concluded that the suggested model outperforms the existing model.

(Dimitrov et al., 2020) [7] Analyze, develop, and perform experiments on an IGBT (Isolated Gate Bipolar Transistor)-based transformerless Buck-Boost DC-DC converter for rapid charging electric automobiles. Main benefits include a simple power stage construction, broad output voltage range, and excellent efficiency and power density for hard-switched converters in this class; this topology is a good fit for today's on-board battery packs in electric vehicles. The converter's fundamental modes of operation – Buck, Boost, and Buck-Boost – are shown to have an exact calculation of the loss that is dissipated. In the Buck-Boost operating mode, the study demonstrates a loss minimization technique based on a decrease in switching frequency. Using this method ensures that the thermal properties of the device remain steady during the battery charging cycle. As a result of the Buck-Boost mode's reliance on semiconductor properties, it might be regarded as a critical mode when Buck and Boost modes alone are unable to maintain the output voltage. The duty cycle and voltage range required, as defined by input-output voltages and power losses, will need more research in this regard. For the most adaptable silicon-based powerful IGBT modules, the tolerance of the applied switching frequencies is evaluated and experimentally validated. An experimental model was used to produce oscillograms of crucial properties, such as transients, IGBT voltage tails, critical duty cycle lengths and more.

(Brenna et al., 2020) [8] Various EV charging systems are described in the literature and put into practise in real-world situations. In terms of converter topologies, power levels, power flow orientations, and charging management algorithms, this study provides an overview of the current and prospective EV charging technologies in this field. Additionally, an overview of common charging techniques is provided, with a special emphasis on a rapid and efficient charging method for lithium-ion batteries that is both effective and efficient in terms of preserving a long cell cycle life. To conclude this study, after presenting the most essential components of charging technologies and techniques and using a genetic algorithm to determine an appropriate charging system capacity, the likely future developments in this subject are evaluated.

(Bharathidasan & Indragandhi, 2020) [9] The broad overview of single-phase AC/DC-DC power electronic converter power factor correction for electric vehicle applications is completely discussed in this article. Propose the use of a variety of solid-state DC-DC converters to improve power quality in the declaration of "Power Factor Correction (PFC)." While comparing DC-DC converters, both the Uni- and Bi-Directional power flow representations are taken into account when trying to reduce "Total Harmonic Distortion (THD)" on the input and output sides. This study contains an in-depth examination of IPQC setup, design features, and selection criteria. Having a converter flow of power capability is required for an on/off-board charger for electric vehicles (EVs). Due to their high power density and efficiency, DC-DC converters are favored for medium and high voltage applications because of their ability to soft-switch. This is the most appealing attribute of DC-DC converters. Research, design, and improvement of functioning applications in the area of renewable energy and smart grids is the goal of this study

(Vijai et al., 2019) [10] In battery charging applications, DC-DC converter performance has been shown to be a solution. Most electric bike battery chargers use a two-stage converter that includes a boost converter for power factor correction (PFC) and a dc-to-dc converter with a universal input voltage.. Because of their inefficiency and additional complexity, these two-stage conversions aren't recommended. Rather of using a DC-DC converter in this project, a SEPIC converter has been used to address the issue. SEPIC converters may reduce DC converter issues such excessive ripple, harmonics, voltage inversion, overheating, and ineffective efficiency while also achieving the highest levels of efficiency. Closed loop feedback control is used to develop and compare DC-DC converters using the SEPIC converter. PFC converter based on a single-stage switching inductor SEPIC converter is recommended as an alternative to the more common DC-DC converter because it has a higher step-down gain, lower current stress, higher efficiency, and requires fewer components. Continuous current mode is used for the operational analysis and design equations for different components of the proposed converter. The planned 48V converter is the subject of this simulation and testing. A battery charging converter with Constant Voltage and Constant Current modes of operation is also studied in terms of the broad range of supply changes.

(Mahalakshmi & Seyezhai, 2016) [11] "Power Factor Correction (PFC) boost converter topologies" appropriate for telecommunications are reviewed in this research. Telecommunication systems might benefit from a revolutionary integrated PFC architecture that provides backup power. The suggested circuit's benefit is that it uses a soft-switching technique to reduce the converter's switching losses. "Conventional average current mode control boost PFC, bridgeless boost PFC, semi-bridgeless boost PFC, totem-pole bridgeless boost PFC, and suggested integrated boost PFC are investigated in this article." PSIM software is used to simulate converter circuits for all of these topology evaluations. The supply power factor, supply current THD, and displacement factor of all topologies have been thoroughly compared. An increased power factor and a lower supply current THD are deduced from the findings of this study. The findings are confirmed.

IV. PROPOSED METHODOLOGY

Fast charging infrastructure is lacking; thus, automakers are relying on on-board battery chargers that can be recharged using a standard wall outlet. For electric and hybrid cars, there is a wide variety of information accessible on charger topologies, power levels and stages.

As seen in Figure 7 the usual structure of battery chargers that can take a broad range of input voltages is shown here. It is necessary to have a front-end active PFC converter at the input to keep the power quality good. Boost converters, either with or without interleaved architecture, are often used in PFC applications because they give a dc output voltage larger than the peak ac line voltage. [38]

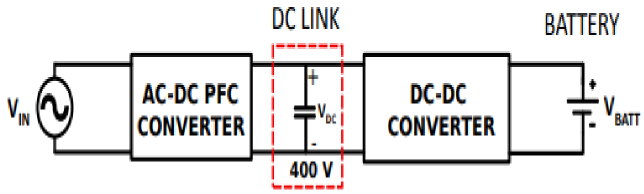

Figure 7 Two-stage layout of battery chargers

It did, however, demonstrate some gains in efficiency, but the organisation of the increase PFC category remained the same. Using a high-frequency DC-DC converter, the PFC converter's output voltage may be used to power a variety of batteries with a minimum voltage of 200 V. "There are few electric vehicles having the DC battery operating voltage less than or equal to 150 V (48 V system, 72 V,96 V,144 V)." The battery charger manufacturers use a high frequency step-down transformer in the DC-DC converters, which limits the output voltage range, transformer weight, and efficiency with restricted ZVS in such a low output voltage state.

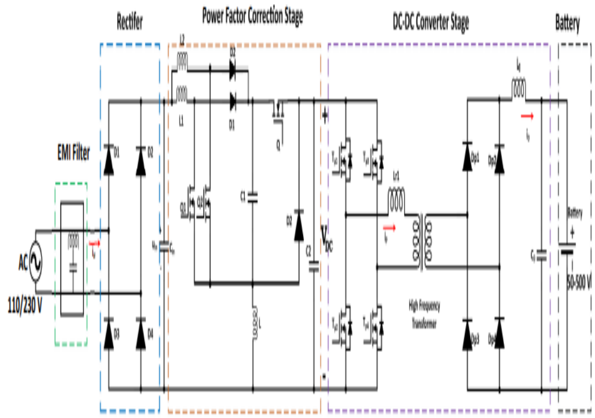

Figure 8 Proposed Interleaved boost cascaded-by buck PFC converter based on-board battery charger

Figure 8 is a schematic for a two-stage on-board battery charger of the kind described above. An isolated DC-DC converter and a power factor correction converter are also included. The interleaved boost and buck converters form the basis of the proposed PFC converter. Non-pulsating current from the inductors L1 and L2 at the input may be readily regulated to preserve power quality.

Reduced input current ripple is another benefit of interleaved combination at the input. Switches Q1, Q2 and diodes D1 and D2 create a boost configuration in the continuous conduction mode (CCM) of the converter. Depending on the operating mode, an LC filter is connected with either the converter's input or output to supply non-pulsating currents to the source and load. Using the input and output voltages, the converter manages the buck switch

Q and diode D. When the input voltage Vmax reaches its peak, the converter's output voltage VDC may be regulated to a value either above or below that value.[40]

Adaptive-Neuro Fuzzy Interference System (ANFIS)

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid intelligent control technique that combines the learning capabilities of Artificial Neural Networks (ANNs) with the reasoning methodology of Fuzzy Logic. ANFIS is particularly effective in modeling nonlinear and complex systems, making it well-suited for control applications in electric vehicle (EV) power converters.ANFIS is built on the framework of the Takagi-Sugeno-Kang (TSK) fuzzy inference model. The architecture of ANFIS typically comprises five layers, each performing a specific function in the fuzzy reasoning process. These layers include fuzzification, rule application, normalization, defuzzification, and output generation. The system uses if–then rules with tunable parameters that are adjusted using neural network training algorithms such as backpropagation or hybrid learning (a combination of least squares estimation and gradient descent).

Key Features of ANFIS:

Fuzzification Layer: Converts crisp inputs into degrees of membership using predefined membership functions (e.g., Gaussian, triangular).
Rule Layer: Applies fuzzy if–then rules to combine inputs.
Normalization Layer: Normalizes the strength of each rule.
Defuzzification Layer: Calculates rule outputs using linear or constant functions.
Output Layer: Aggregates the outputs to produce a final crisp value.
Advantages in EV Converter Control:
1.Robust Nonlinear Modeling: ANFIS can learn and adapt to nonlinear characteristics of EV converters.
2.Fast Convergence: The system adapts quickly due to hybrid learning algorithms.
3.Reduced Steady-State Error: Provides finer control and more accurate output voltage regulation compared to conventional PI controllers.
4.Low Total Harmonic Distortion (THD): Enhances power quality by minimizing source current distortion.
5.Flexibility and Scalability: ANFIS can be easily extended for multi-variable systems and higher-order control applications.

In the context of EV battery charging systems, ANFIS is used to regulate the switching of power electronic converters such as interleaved boost and buck stages. It adjusts the duty cycle dynamically based on real-time inputs like voltage error and change in error, enabling precise control over the output voltage and power factor.The base of ANFIS is the Takagi-Sugeno-Kangmodel (TSK), often known as the Sugeno fuzzy model, ANFIS's five-layer design has two kinds of nodes—fixed and dynamic .Nodes outside of the membership function layer and the subsequent layer are fixed.

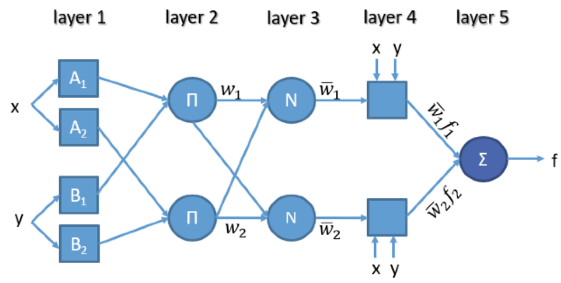

Figure 9 ANFIS architecture

V. CONCLUSION

This review has comprehensively analyzed various converter topologies and control strategies employed in electric vehicle (EV) battery charging systems. Among the examined solutions, interleaved boost cascaded-by-buck converters have emerged as a highly efficient topology capable of handling a wide range of output voltages while maintaining high power quality. Additionally, intelligent control techniques such as Adaptive Neuro-Fuzzy Inference System (ANFIS) demonstrate significant improvements over conventional PI controllers in terms of reduced voltage ripple, faster transient response, and improved total harmonic distortion (THD) performance. The integration of ANFIS with advanced converter architectures ensures near-unity power factor operation, making it highly suitable for both onboard and offboard EV charging systems. Future research should focus on real-time hardware implementation, optimization of controller training algorithms, and integration with renewable energy sources to enhance the sustainability and reliability of EV charging infrastructure.

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