Review Article

Shunt Active Power Filter: A Review

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Abstract: This paper examines a comprehensive and systematic review of the published work proceeding on the progressive decrease of switches for smart battery chargers with the APFs configuration. The key characteristics of the cutting-edge technology in RES, dual active bridge converter with functions of active power filter (APF), and electric vehicle (EV) battery charging system have been elaborated in this research. Following with the problem description and objectives of this study are articulated. A thorough categorization of conference papers, journal articles, and transaction publications is conducted, centering on comparisons within the realm of electric vehicle EV and APFs power grid applications. This paper emphasizes scrutinizing EV battery chargers for operating a novel battery design and topologies with reduced switch count topologies. The primary focus of this paper is the compilation of relevant publications pertaining to advanced reduced switch count topologies and intricate control schemes designed for redesigning voltage source inverters (VSIs). Additionally, a detailed assessment of the latest advancements and accurate qualities are discussed and presented.

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Introduction

Countless solid states converters generate reactive power component due to non-linear loads. This results in a high number of current harmonics in the power grid. These harmonics damage the overall system performance and stability of each component and power module. Several EV systems coupled in series or parallel configuration to the power grid network, which creates a high amount of electronic switches losses due to the high number semiconductor components (Veerendra *et al*., 2024). This indicates the failure of the system efficiency and deteriorate the sinusoidal current and voltage waveforms (Fatemi *et al*., 2013; Nguyen *et al*., 2018; Zhu *et al*., 2023). However, the EV battery charger with the capability of SAPF circuit eliminates these odd and even harmonics in the current and voltage waveforms. This results in the utilizations of the large number of components or modules using the high-power rating leads to system damages and thermal issues (Acar *et al*., 2024; Akbar *et al*., 2022; Diab *et al*., 2016; Hou and Emadi, 2017a, b; Pires *et al*., 2019). In these hybrid EV systems, the limitation of using a inductor and capacitor (LC) passive filter in series or parallel coupling circuits (Amir *et al*., 2024; Chakraborty *et al*., 2023), generates an certain magnitude of fundamental primary current (Muduli *et al*., 2023). Also, the constant design values of the LC filters limit the filtering range for harmonic eliminations and reactive power regulation (Lenka *et al*., 2024; Reddy *et al*., 2024; Taghizadeh *et al*., 2018). In some cases of hybrid or standard EV-APF systems start the problem of series resonances, and limited, and uncoordinated battery pack charging (Chandra *et al*., 2024; Jiao *et al*., 2018; Lenka *et al*., 2024; Rodrigues *et al*., 2022; Zhang *et al*., 2010). Several EV batteries charging configurations are available in the market, (a) Universal battery charging system (b) Grid-connected PV-EV battery charging system (c) Stand-alone PV-EV battery charging system and (d) Grid-connected WTG-EV battery charging system (Karneddi and Ronanki, 2023; Liu *et al*., 2023). Figure 1 demonstrates the PV standalone system as off-board chargers topology for power the EV batteries, with no use of grid. An additional, bulky battery storage unit is necessary due to the irregular and alternating nature of the sunlight (Sora *et al*., 2024). The extra battery bank will keep the overall power of the system constant and discharge to power the EV battery (Yi *et al*., 2023). Without installing the battery bank this circuit be able to operate as an on-board charger system (Srivastava *et al*., 2023). Figure 2 demonstrates the off-board EV charger as connected with the power grid. Both PV and grid power can be worked to power the batteries. In this topology, a bidirectional inverter is installed between the AC and DC bus system. This inverter transfer energy in both directions between the AC and DC buses. Additionally, the benefit in this EV charger configuration is that the excess or unused power can be directed in both directions towards the grid throughout the peak daylight hours from the PV array and in some cases from the EV batteries. Furthermore, during the absence of sunlight radiation, EV batteries will be adopted to power the grid. This inverter will act as a rectifier when transferring power from AC to DC, and as an inverter from DC to AC between the PV and power grid (Hansen *et al*., 2000; Muqeet *et al*., 2023). Figure 3 illustrates an off-board EV charger and works as a grid tied WTG-EV battery charging system. The wind generator with the power grid charges the EV batteries. This battery charger will work like a PV charging system and perform the operation in bidirectional approach (Govardhan and Atkar, 2022; Wang *et al*., 2022). In summary, several bridgeless topologies such as buck-boost, boost, single ended primary inductance converter (SEPIC), pseudo boost, and cuk converters are demonstrated in the Table 1. It summarizes the applications of these converters based on number of counts and less losses in the battery charger system (Bharathidasan and Indragandhi, 2020; Gonçalves *et al*., 2021; Kumar *et al*., 2024; Vishnuram *et al*., 2023).

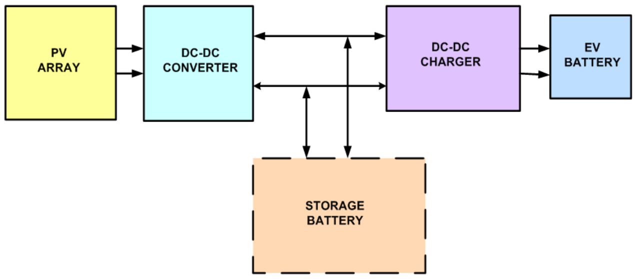

Figure 1: *Stand-alone PV-EV charger.*

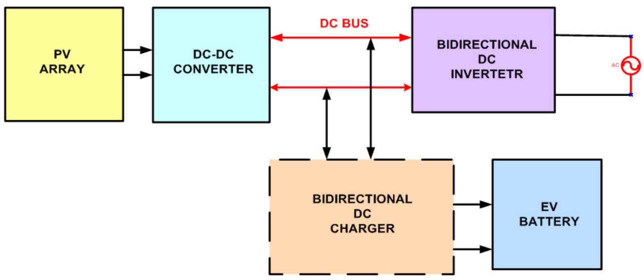

Figure 2: *Grid-tied PV-EV charger and power grid.*

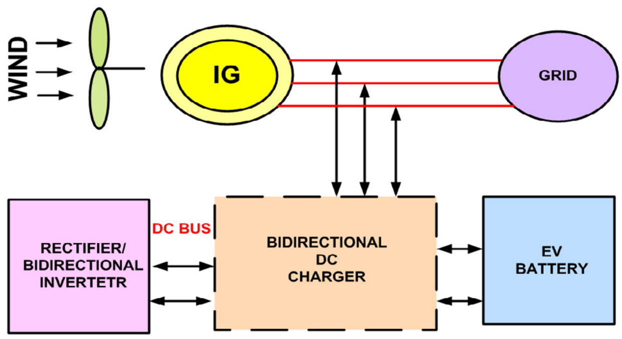

Figure 3: *WTG-EV battery charger.*

PQ in local generation systems

APF and PV energy power grid: The proliferation of RE devices in power transmission networks produces various challenges in PQ for researchers and engineers. The primary objective of introducing integrated PV

Table 1: *Comparison of AC/DC PFC converter topologies (Bharathidasan and Indragandhi, 2020; Gonçalves et al., 2021).*

Parameters	Conventional PFC converter	Bridgeless topologies				
		Boost PFC converter	Buck-boost PFC converter	Pseudo-boost PFC converter	SEPIC PFC converter	Cuk PFC converter
Structure complexity	Moderate	Simple	High	Simple	High	High
Efficiency	Low	High	Low	High	High	High
No. of switches	1	2	3	1	2	2
No. of diodes	5	2	4	2	2	2
No. of capacitors	1	1	3	2	3	4
No. of inductors	1	1	1	2	3	3
Cost	Moderate	Low	Moderate	Low	High	High
Advantages	Simple control circuit	(1) Less number of semiconductor devices, (2) Low loss, (3) Simple control circuitry	Efficient in producing regulated DC voltage.	Low switching losses	Low Conduction losses and thermal stress on the semiconductor device	(1) Low conduction and switch losses, (2) Low switching current stress, (3) Low common mode noise
Disadvantages	High loss due to the diode bridge circuit	(1) High electromagnetic emission, (2) High inrush current	Controlling circuitry is complex.	Design of resonant circuit is complex.	Traditional electrolytic capacitor cannot be used	Floating switch present in this topology requires a more complex driver circuitry

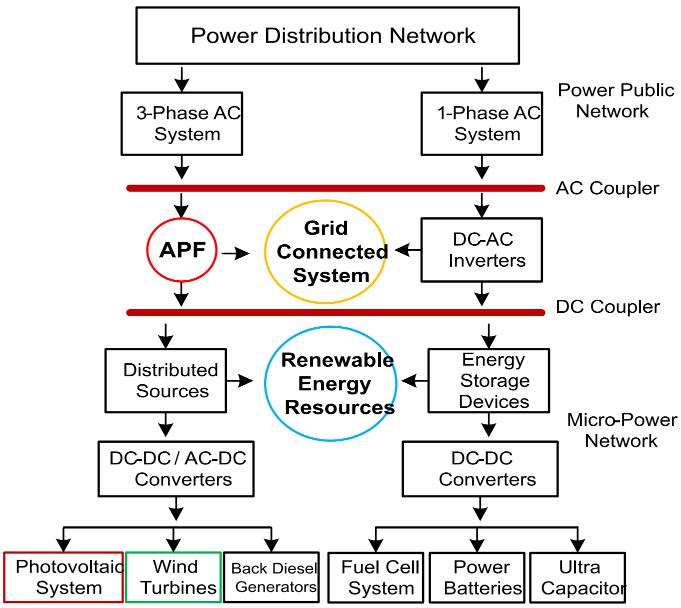

Figure 4: *Classification of RES and local grid system.*

systems at the point of common coupling (PCC) is to enhance the running of the local distribution grid by injecting high quantity of active energy (Du *et al.*, 2023). To reduce the system cost and size, a several PV grid shared circuit topology are incorporated with the PV inverter having improve and better functionalities, such as SAPF capabilities (Govind *et al.*, 2024), and reactive power support as well as voltage. Consequently, the PV inverter inserts neutralizing currents as compensation into the power grid against the rectifier load harmonics (Ahmadzadeh *et al.*, 2024; Pelz *et al.*, 2024). In addition, it utilizes the active power generated by the solar PV system. Simultaneously, APFs known for their adaptive functionality and advancement are installed into the PV system to enhance the overall system effectiveness, improve dependability, and address the current harmonic problems in distribution systems (Rezapour *et al.*, 2024; Wang *et al.*, 2024). Figure 4, demonstrates the categorized arrangement of RE, incorporating different power storage resources into a local distribution grid (Tareen *et al.*, 2017).

In recent times, the multilevel multifunctional inverter (ML-MFI) has emerged as the predominant tools in the grid-tied inverters with PV and other RESs for power production. It operates at very high DC-rated voltage and generates low HD waveforms in steps as the output. Effectively, addressing different and enormous MFI challenges for example unbalanced correction, current harmonics, reactive power, manages grid-tied RES transient, control voltage at the PCC and APF operation (Barghi and Teke, 2015). ML-MFI topologies discover applications in the excessive rating PV systems due to their numerous advantages, including low HD, reduced energy dissipation, and outputs with minimal electromagnetic interference (EMI). The number of switches in the overall system will reduce the volumetric size, and system cost. The reduced number of switches will decrease the switching losses and improve the overall system efficiency. Table 2 provides a summary of the difference between PV inverter grid topology with the feature of APFs functionalities (Boscaino *et al.*, 2024). However, from the research it has been observed that eliminating the transformer, introduces many challenges, such as low efficiency, several safety concerns, leakage current, and the need for resonant circuit installation (Mahmud and Gao, 2024; Rajesh *et al.*, 2024).

Table 2: *Evaluation of APF topologies.*

Parameters	Shunt Active Filter	Series Active Filter	Hybrid APF
Circuit configuration	Figure 2.9 (a)	Figure 2.9 (b)	Figure 2.9 (c)
Power range			
Small scale	<350 W (power ratings below 100 kVA)		
Medium scale	<350 kW (three-phase systems ranging from 100 kVA to 10 MVA)		
Large scale	<350 kW (systems with ratings above 10 MVA)		
Converter efficiency			
Small	Lowest (up to 98%)		
Medium	High (up to 98%)		
Large	Highest (up to 98%)		
APF operates as	Current source (CSI)	Voltage source (VSI)	Both (CSI/VSI)
Current harmonics	**	-	***
Reactive power	***	-	**
Neutral current	**	-	*
Voltage harmonics	-	***	**
Voltage regulation	*	***	**
Voltage flicker	***	**	-
Voltage sag and dips	*	***	**
		High number of "*" is preferred	

Various combinations of power converter configurations are shunted at the PCC to line the RES as utility with the grid. These configurations are controlled with various modulation arrangements. However, PV grid-connected system offers improvements in the voltage, frequency as judged to fixed network topology, general method voltage decreases and leakage current. In study (Mahela and Shaik, 2016; Song *et al.*, 2024; Tsengenes and Adamidis, 2011), a three-level neutral point clamped multilevel full-grid-connected inverter (NPC-MFGCI) PV system is presented. It is effectively controlled by using an altered and revised voltage-learning controller and space vector pulse width modulation (SVPWM) technique. This control strategy enhances the system's performance by providing SAP filtering, reactive power compensation, and balancing load currents supplied to the power grid. The integration of a SAPF with a PV grid-connected system serves the dual purpose of eliminating harmonics and balancing reactive power to continue a constant DC-link voltage (Divya *et al.*, 2024). It is obvious to have an ambiguous and self-sufficient mathematical model to address various parameters (Ray *et al.*, 2016). In contrast, energy storage systems, including batteries, flywheels, and supercapacitors, are strategically employed to deal with the irregular challenges in RES-PV systems. The operational qualities of PV systems can lead to a decrease in power generation by up to 15% per second, impacting the overall performance of the grid network. hence, energy storage systems plays a crucial role in maintaining constant voltage, reducing voltage fluctuations, and enhancing PV productivity (Hossain *et al.*, 2023; Kureel *et al.*, 2024). Collectively, PV systems contribute to suppressing harmonic content and help in regulating the reactive power compensation. Thus, improving the general dependability of the grid-tied systems (Zhou *et al.*, 2020).

APF and wind energy power grid

Nowadays, the energy industry has been increasingly favoring the adoption of RE. Wind energy has emerged as a more supportable, cost-effective power source that remains available throughout the year. When compared to non-renewables and solar power, wind energy stands out due to its affordability, net-zero emissions (GGEs), status as a growing source of RE, accessibility, and escalating flexible production. Consequently, meeting energy demands becomes achievable in an environmentally friendly manner at the PCC for local grid network. Yet, addressing poor PQ poses a complex challenge in grid-connected wind energy conversion systems (WECS) (Shao *et al.*, 2024). The increased demand for integrating wind turbines (WTs) with the main grid has notable effects on reactive power, intense voltage variations, and current flash at the PCC, primarily due to switching operations (Selvam *et al.*, 2024). The controlling of variable-speed WTs relies on the controller of the active and reactive power, highly influenced by the characteristics of nonlinear and unbalanced loads. In this links, the power electronic components with nonlinear behavior led to the generation of extremely high THD in current and output voltage, thereby compromising the running of the WTG (Kureel *et al.*, 2024). This situation results in increased heat, degrades the efficiency of the system, and shortens the lifespan for the WTG (Debdouche, Benbouhenni, Deffaf, Anwar, and Zarour) Consequently, the need to implement suitable harmonic filtering and reactive power regulation has become imperative for enhancing the PQ of wind speed energy in grid-connected systems (Hernández-Mayoral *et al.*, 2024).

A WTG functions by maintaining a continuous wind velocity to regulate the permanent magnet synchronous generator (PMSG) for the purpose of mitigating current harmonics (El-Kadeem *et al.*, 2024; Hernández-Mayoral *et al.*, 2024). To achieve this, an advanced modulation technique, specifically known as direct controlled modulation method, is employed to manage the APF system using various reference signal as extraction methods (Govind *et al.*, 2024). An upgraded variable frequency-based Wind Turbine System (WTS) operates in islanding mode to eliminate harmonics (Aljarrah *et al.*, 2024). In study, (Ahmed *et al.*, 2013; Aljarrah *et al.*, 2024; Debdouche *et al.*, 2024; Khalafian and Saffarian, 2024), the doubly fed induction generator (DFIG) in stable and attached speed incorporates the WT with the capabilities of APF. To address voltage imbalance and reduce converter costs, a WECS system utilizes a reduced-switch-count topology with split-capacitor leg configurations (Mahmud and Gao, 2024; Selvam *et al.*, 2024). Nevertheless, this network topology presents uncoupling challenges among the local grid and multipole PMSG systems, requiring an additional DC-link capacitor with control and increases semiconductor stress (Wang *et al.*, 2024).

In wind energy conversion system (WECS)

connected to a grid, Parameters like reactive power control and compensation are basic and essential needs in power distribution grid. Maintaining a constant voltage profile for the WTG is essential to minimize losses during the exchange of reactive power with the power grid. The primary device for controlling reactive power gains into the power grid is a under load tap changer transformer. However, some WTs system produces a little to limited reactive power and voltage in the coupled induction generator (Khalafian and Saffarian, 2024; Lima *et al*., 2010; Rajabi *et al*., 2024; Tilli *et al*., 2019). To address these issues, various devices, including static synchronous compensator (STATCOM) (Kureel *et al*., 2024; Liu *et al*., 2024; Valdez-Fernandez *et al*., 2024), on-load tap changers (OLTC) (Jiang *et al*., 2024), static var compensators (SVCs) (Kureel *et al*., 2024), PWM inverters (Vázquez and Vaquero, 2024), switching capacitors, and complex combinations of capacitors and inductors (Lin *et al*., 2024; Rao *et al*., 2024), are integrated with induction generators. Some devices, like dynamic braking resistor (DBR), manually switched capacitor banks and OLTC, struggle to overcome harmonics and voltage flicker. Conversely, devices like distribution static synchronous compensator (DSTATCOM), STATCOM, SVC, and doubly fed induction generator (DFIG) enhance the stationary and active strength of reactive power in fixed-speed wind generators (Khalafian and Saffarian, 2024; Selvam *et al*., 2024; Watanabe *et al*., 2024). These devices contribute to regulating voltage balance, thereby facilitating, and encouraging the utilization of wind energy in local grid systems. Reactive power gains procedures, as outlined in several studies (Nomura and Hatakeyama, 2024; Tan *et al*., 2006), are related with more parameters (Zhan *et al*., 2024). The controller limits associated with reactive power gain devices include dynamic voltage restorer (DVR), automatic voltage control (AVC), series dynamic braking resistor (SBBR), static VAR compensators (SVC), thyristor-controlled series capacitor (TCSC), on-load tap changer (OLTC) and unified power flow controller (UPFC) (Moghassemi and Padmanaban, 2020).

Methods for reducing harmonics

Old-style devices for reducing harmonics: In the future, several methods have been employed to address harmonic content issues in power distribution systems that are coupled to the power grid. This section discusses enhanced tools for PQ and harmonic difficulties, focusing on PFs and APFs (Afkar and Esmaeeli, 2023; Morán *et al*., 2024; Patel *et al*., 2023).

Shunt passive filters: The PFs were initially proposed as a primary answer to address a PQ problem in the power grid arrangements. It provides a straightforward and cost-effective approach, employing various sequences and similar arrangements of inductors, damping resistors and capacitors (Das *et al*., 2023; Karadeniz *et al*., 2023). The commonly employed configuration of PFs, as illustrated in Figure 5, relies on specific values of inductance and capacitance to determine filtering characteristics. Every single function is affected by the fundamental source impedance and is regulated to specific harmonic orders, such as the first, second, and third orders, to effectively mitigate the targeted harmonics.

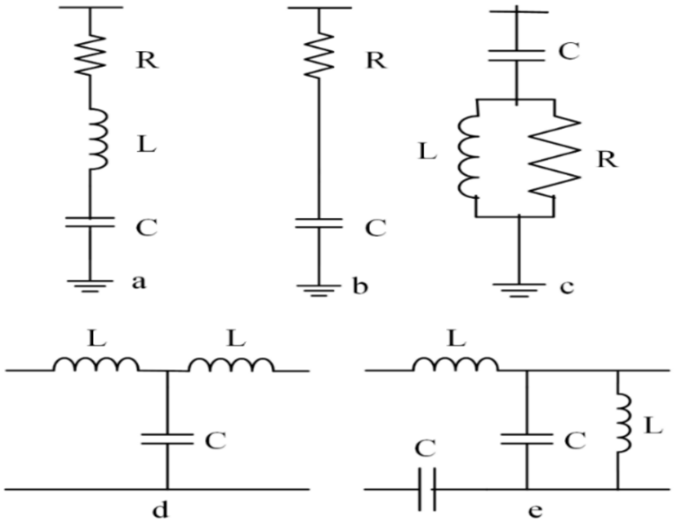

Figure 5: *Categories of PF (a) Single tuned filter, (b) First order high pass filter, (c) Second order high pass filter, (d) LCL filter, (e) LLCC filter.*

The literature review encompasses various PFs design methods, including the series filter, LCC filter (He *et al*., 2024), single-tuned filter (Hsiao *et al*., 2024), shunt filter, double-tuned filter (Stanley, 2024), low-pass filter (Nako *et al*., 2024), high-pass filter (Ma *et al*., 2024), and band-pass filter and LCL filter (Aslankaya *et al*., 2024). The series PF configuration is integrated into the power grid system in series to introduce great impedance for cancelling the current harmonics. Typically, for improved harmonic compensation and controlling of reactive current components, PFs are superior tied technology with thyristor-controlled reactors (TCR) (Vijay *et al*., 2024; Watanabe *et al*., 2024). While some limitations of shunt PFs are affected by the quasi-types PFs (QPF) (Malki *et* al., 2023). The major and most important practical limitations (Rezapour et al., 2024) are explained as follows:

1. Each harmonic current requires a separate filter, restricting the filtering range.
2. The fundamental current or harmonics component are allowed by the PFs during in single operation.
3. Superior levels of current harmonics overfill the PFs, triggering a series resonance that leads to extreme volume of harmonics components.
4. The parallel and series negative resonance leads to source-side harmonics amplifications among the grid and filter impedance (Ding et al., 2024).
5. In AC systems, the adjustable load circumstances change the PFs design parameters due to change in system operational frequency.
6. PFs operate at tuned frequencies, causing them to operate in limit frequency range compensation and big size and regulating challenges.

Shunt active power filters: In response to the limitations of PFs, APFs have been introduced and extensively studied. These filters comprise an active switching device along with passive energy storage components like inductors and capacitors. They help in offering compensation in addressing issues such as unbalanced voltage for utilities, voltage and current harmonics and current difference for customers. Furthermore, APFs control reactive power, neutral current, changing line impedance, frequency difference, removal of voltage levels, direct voltage alterations, voltage flicker suppression, short and sudden disturbances, unity power factor (UPF) improvement (Kureel et al., 2024), and voltage balance (Qasim et al., 2023). Additionally, researchers have proposed and explored various APF topologies and control methodologies to address crucial problems in load applications with high-power (Rezapour et al., 2023; Sztajmec and Szcześniak, 2023). APFs are categorized based on several important measures. Typically, an APF circuit operates on a more promising technique called a pulse width modulation (PWM) inverter with a DC-link capacitor. From research and studies, it is observed that the APF's current source is higher in terms of mitigating current activities. While the performance of the APF's voltage source is one step ahead in maintaining lower carrier harmonics of PWM and improved losses by the filters. Figure 6 demonstrates the fundamental compensation concept of the three-phase shunt APF for removing current harmonics. In general, APFs are positioned near nonlinear loads in shunt position to counteract the effects of harmonic non-linearity. Non-linear loads generate current harmonics that drive back toward the grid. The basic role of the APF's is to protect the utility by removing these harmonics and inserting reactive or counterbalance current at the PCC. It produces inverse harmonics that act as a mirror reflection to the nonlinear load harmonics, effectively neutralizing current harmonics and safeguarding the fundamental component, thereby maintaining a pure sinusoidal source current.

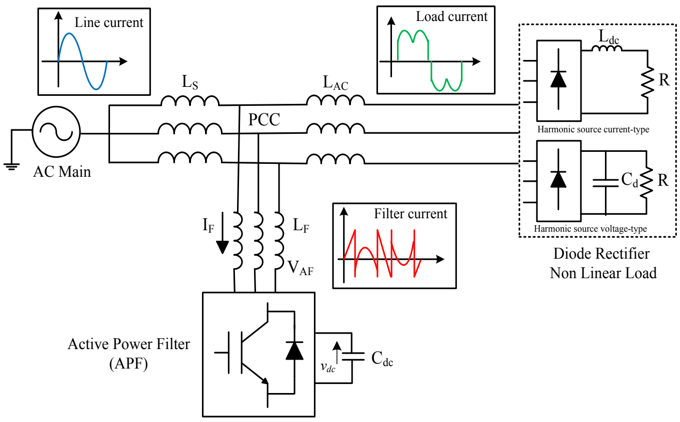

Figure 6: *Power grid coupled SAPF system.*

Types of power grid coupled APF systems

In general, APFs are categorized into two main types: AC power filters (Dash and Sadhu, 2023), and DC power filters. AC power filters encompass various active solutions, including active PQ conditioners (APQC), instantaneous reactive power compensators (IRPC) (Yi et al., 2023), plus active power line conditioners (APLC), to address various harmonics generated by current and voltage (Chavan et al., 2023). On the other hand, DC-APFs are typically implemented with thyristor arrangement and find applications in high-energy applications (Zhang et al., 2023), and high-voltage DC systems (HVDC) (Chandio et al., 2023). SAPF specifically, are classified into three main configurations: Network topology-type, circuit converter-type, and circuit phases-type. The classification based on the amount of wires (phases) includes two wires (single-phase), three wires (three-phase), and four wires (three-phase) systems (Freitas et al., 2023). Figure 7 show outline of the hierarchical structure of the classification of APFs (Boopathi and Indragandhi, 2023).

Depending upon the topology, it is further sub-divided into three main types: SAPF, series APF, andHAPF configurations, as illustrated in Figure 8.

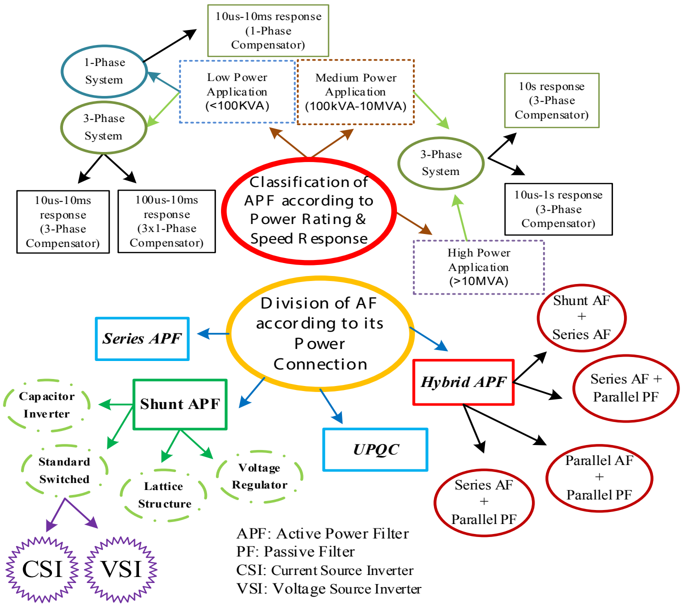

Figure 7: *Different types of APFs.*

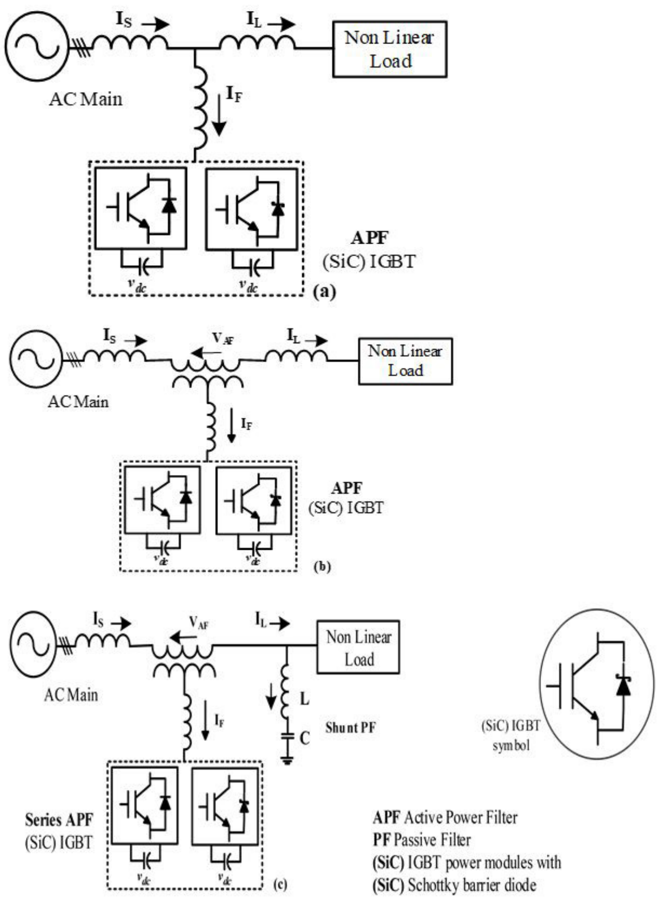

Figure 8: *(a) Shunt APF (b) series APF (c) Hybrid APF.*

The series APF is specifically engineered to alleviate the adverse effects of negative voltage harmonic circulation induced by circuit resonance (Zhang *et al.*, 2024), leading to an enhancement the terminal voltage in the electrical services. In the power sector the escalating need for load current results in current loss and limitations in filter dimensions. The HAPF is the combination of pure APF with the hybrid APF systems. Developed a difference between the coupling components of inductors L_s and capacitors C_s, linked with the main distribution system. The importance of integrating HAPF within the battery charger topology is to reduce the overall rating of the switching devices in the inverter. Therefore, it will help in reducing the overall system cost. Table 2 provides a similarity of the different network topology of APF (Jha and Shaik, 2023; Pakhare *et al.*, 2024).

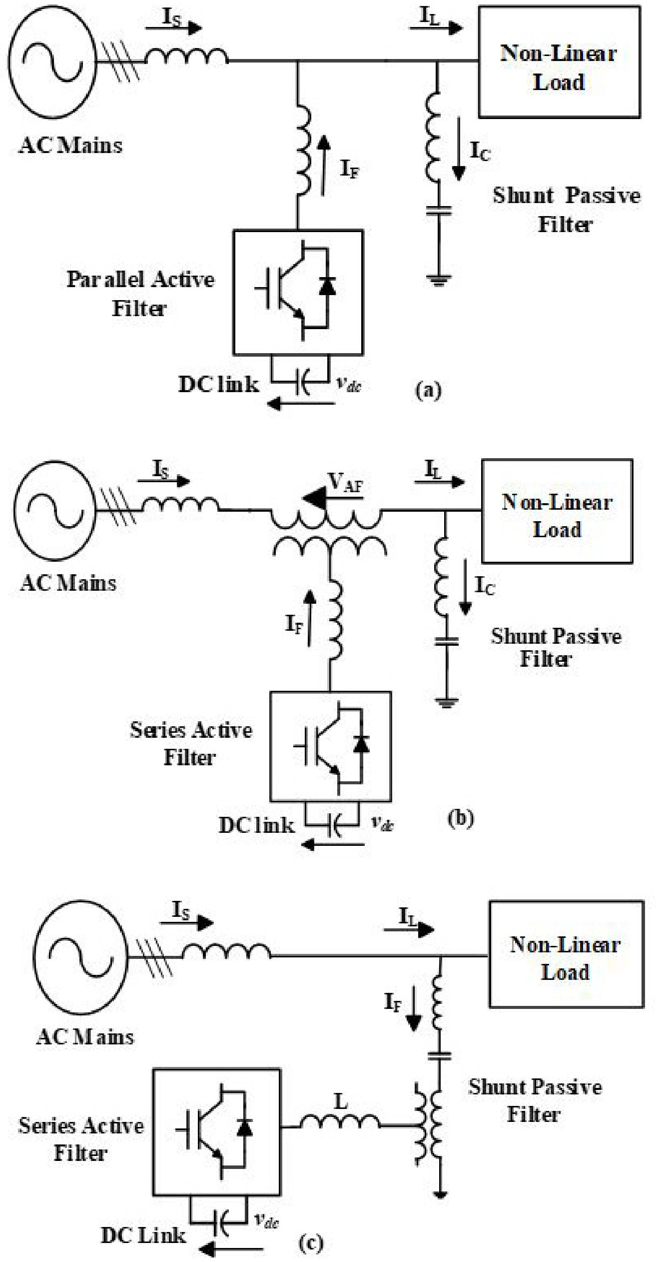

Figure 9: *(a) Coupled shunt APF+shunt PF, (b) Coupled series APF+shunt PF (c) Coupled series APF+shunt PF.*

Figure 9 illustrates three distinct configurations of HAPF circuits associated with the systematic connections to power grid systems, categorized as series, shunt, and combinations of series and parallel like UPQC (Jha and Shaik, 2023). In Figure 9b, illustrates distinguished impedance for total harmonic separation for systems with medium-voltage when coupled in series APF with shunt PF. Results shows that it gives reactive power, a stable three-phase voltages and makeup for voltage harmonics (Mayilsamy *et al.*, 2023). Figure 9a depicts the use of SAPF beside shunt PF to remove the fundamental reactive power and eradicate load current harmonics of greater order. This setup is particularly effective in high-power applications, offering reactive power compensation with reduced switching costs (Verma *et al.*, 2024). For applications with medium- and high-voltage, Figure 9c, involves maintaining constant DC-link voltage and grid fundamental voltage using series APF with shunt PF. This arrangement successfully lowers the overall system size and price (Kureel *et al.*, 2024).

Conventional three-phase APFs

Typically, a standard APF comprises a three-leg bridge structure voltage source inverter (VSI) with a DC-link capacitor (Khadse and Beohar, 2024). Traditional APF configurations necessitate a transformer and a substantial integer of switch devices i.e., IGBT, leading to drawbacks like increased weight and high system costs. Consequently, these topologies are deemed undesirable. In several study (Dash and Sadhu, 2023; Debdouche *et al.*, 2013; Lascu *et al.*, 2007; Rahmani *et al.*, 2012; Srita and Somkun, 2023; Tareen *et al.*, 2017), a non-linear diode rectifier load is powered by the transformer-less conventional SAPF system. Figure 10a illustrates the electrical circuit of the traditional SAPF. Positioned in the shunt configuration at the PCC within the power grid system, the SAPF connects through a coupling inductor. This topology features a total connected six-switch in the full-bridge VSI circuit with DC-link capacitor. Generally, in three-phase traditional SAPF VSI relates to the power grid by installing a set of pairing inductors (L_F filters). The AC-link inductors, specifically designed for shaping the grid current and as well as filtering of current harmonics. Mentioned in study (Han *et al.*, 2010), a three-phase system to compensate the harmonics. Therefore, the SAPF controls the harmonic and fundamental components of the load currents to generate the compensating current. The HAPF are a cost-effective filter system which combines passive and active devices to address the current harmonic filtering and voltage control adjustment problems (Kim and Enjeti, 2002; Zobaa, 2013). The configuration of HAPF consists of series inductor and capacitor (LC) filter instead of the shunt APF AC-link coupling inductors connected in series, as explained in Figure 10b (Xiang *et al.*, 2020). This modification drops the VSI rating power of the DC-link voltage. The shunt APF eliminates low-order harmonics (Lam *et al.*, 2013; Qian *et al.*, 2008), while PFs handle higher frequency harmonics (Lam *et al.*, 2016; Lin *et al.*, 2024; Salmeron and Litran, 2010). However, the series PFs behaved in the circuit introduce a leading current flow which is unavoidable into the APF system. It affects the system performance by limiting the control of reactive power injection into the grid. It happens because of coefficient values of LC PF, a major drawback of conventional HAPF systems.

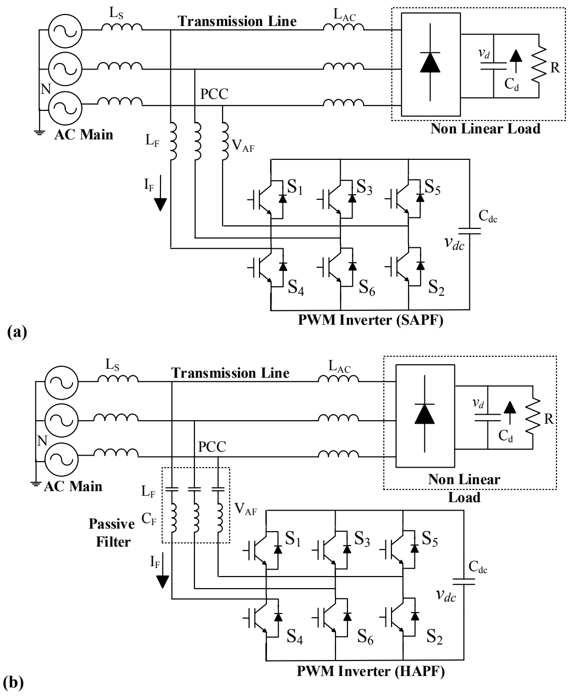

Figure 10: *(a) Inductor type pure shunt APF. (b) Inductor + capacitor type hybrid shunt APF.*

Leading-edge innovations topologies

Reduced switch count EV, RES and APFs inverters: The emerging trend in power electronics focuses on reducing the use of large quantity of semiconductor modules. For example, IGBTs or MOSFETs switches to achieve low costs for VSI system. Designing an economical topology with benefits of having reduced number of semiconductor devices, especially with minimum kilowatts and above, is an appealing goal for researchers. The transformer-less APF system has undergone substantial development, attaining a fully-fledged level, thanks to the progress in microprocessors, rapid-switching devices, and controllers. Smart APF systems with high-rated megawatt values have been proposed, benefiting from less use of switches in inverter network topologies that reduces overall system costs, dimension size, switch losses, control complexity, and interface circuit intricacies. Notably, there is a shift towards orderly modulation techniques to ensure extreme reliability, quick transient, minimum THD, progressive response and stability against sudden load variations. Additionally, these techniques aim to be less in sensitivity to DC-link voltage variations and less alteration in the undisciplined inverter phase. Recent ongoing developments in HAPF target to develop more reliable, leading systems with lowest power rated components with added benefits of dual functionality. This is especially for lower rating industrial appliances, such as APFs, uninterruptible power supply (UPS), motor drives with variable-speed, static frequency changers, etc. In research price saving is a crucial consideration in designing power converters (Dakka *et al*., 2024; Jang *et al*., 2024; Lohia *et al*., 2008). Testing a power converters/inverters design with less quantity, as detailed in Table 3 (Baroudi *et al*., 2007; Kahwa *et al*., 2019; Kubendran *et al*., 2022; Shayeghi *et al*., 2022), providing a comprehensive comparison of various DC-AC inverters across different parameters and characteristics.

Table 3: *Types of DC-AC inverters circuits (Baroudi et al., 2007; Kahwa et al., 2019; Kubendran et al., 2022; Shayeghi et al., 2022).*

Topologies	Electrical isolation	Efficiency (%)	Advantages	Disadvantages
-Single bus inverter with two paralleled half bridge	No	-	-Minimum component count	-Large DC filter components
-Dual bus inverter with two split half bridge single	No	-	-Reliability and flexibility	-High component count
-Phase (3 wire) inverter	Yes	-	-Small passive component	-Complex control; for non-isolated circuit
-Dual phase inverter with transformer	Yes	-	-Boosting capability	- Higher cost and size
-Three-phase PWM inverter	Yes	~98%	-Simple design and control	-
-High frequency link inverter	Yes	~96%	-Boosting capability	-Highly complex; higher cost and size
-Z source inverter	No	~98%	-Boosting capability; save cost, no need for extra DC-DC converter	-Complex control; current stress is high

Recently, advancements and research in power electronics converters have focused on minimizing system magnitude and price while enhancing overall system reliability by focusing on minimum use of switching devices. The modified APFs inverters are further categorized into different topologies depending upon the total application of switches circuits. such as, AC-AC power converters, split DC-leg inverter, and parallel inverters. Figures 11-19 summarizes the entire cycle of reduced switch count installed with the single-phase and three-phase

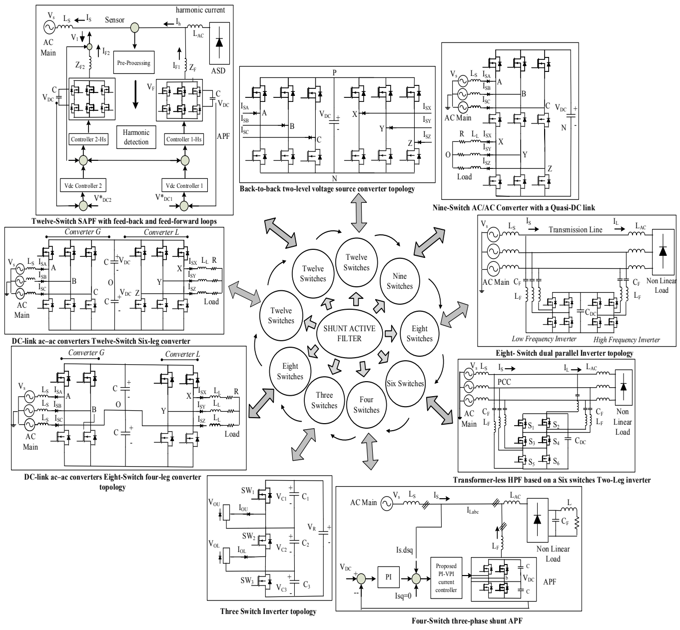

Figure 11: *12- switches SAPF with feedback and feedforward control.*

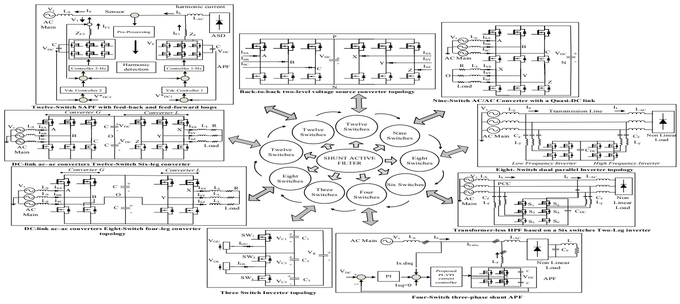

Figure 12: *12-switches 6-legs DC-link AC-AC converter.*

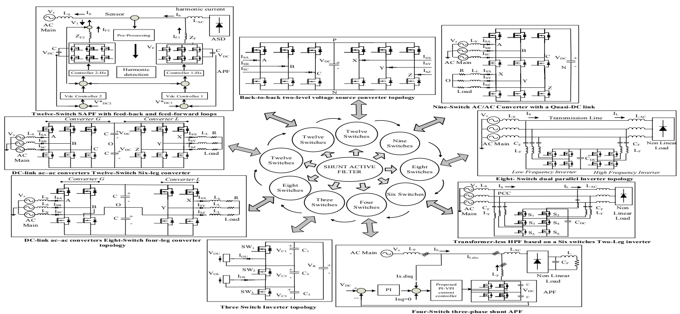

Figure 13: *8-switches 4-legs DC-link AC-AC converter.*

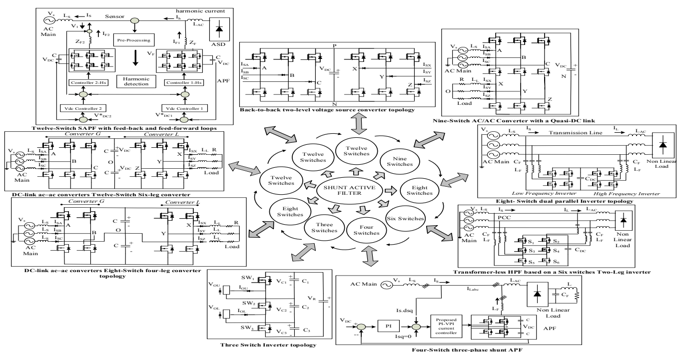

Figure 14: *12- switches 6-legs Back-to-Back VSI.*

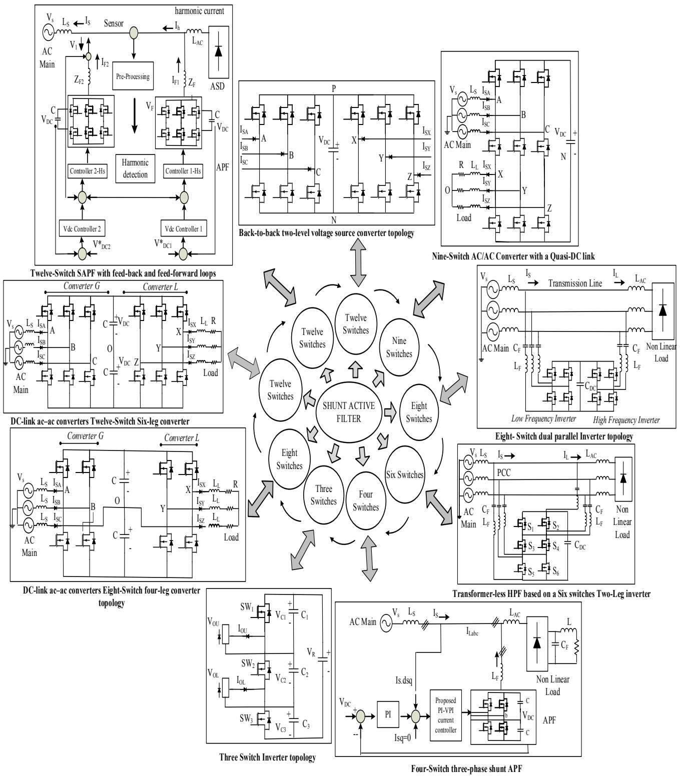

Figure 15: *9-switches 6-legs Back-to-Back VSI.*

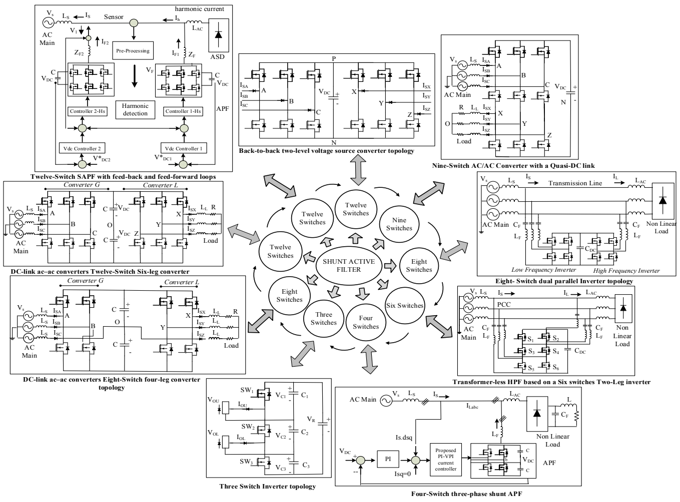

Figure 16: *8-switches 4-legs dual parallel VSI.*

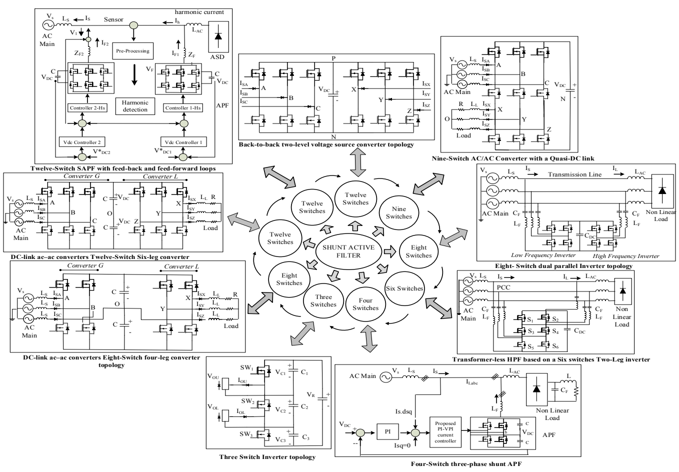

Figure 17: *6-switches 2-legs transformer-less HAPF.*

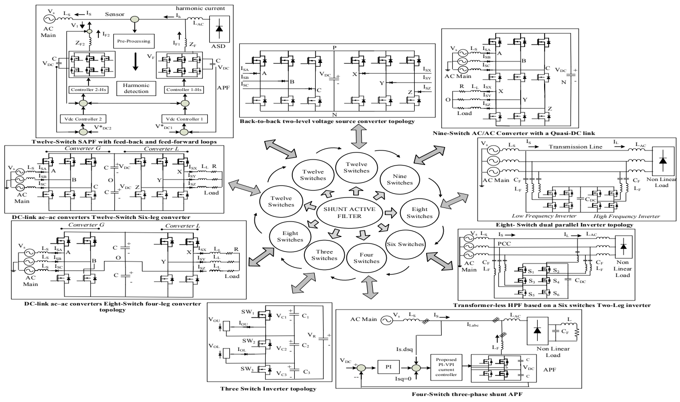

Figure 18: *4-switches 2-legs three-phase SAPF.*

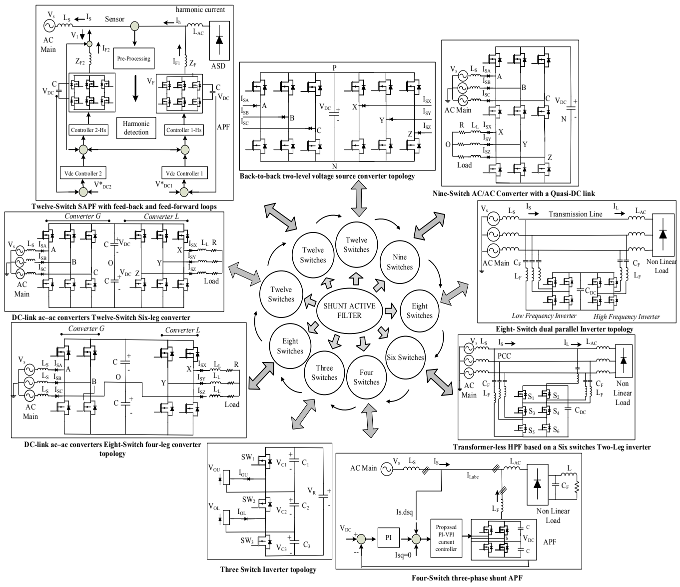

Figure 19: *3-switches 2-legs three-phase SAPF.*

power grid applications, ranging from dozen to three switches. Multiple parameters of power converter topologies, based on volumetric size, losses and operation is highlighted in the Table 4 (Baksi *et al*., 2021; Baroudi *et al*., 2007; Gopi and Sreejith, 2018; Safayatullah *et al*., 2022; Tripathi *et al*., 2015). A novel multi-level power factor correction (PFC) converter designed for unidirectional wireless power transmission, specifically designed to charge EV batteries. The innovative converter achieves a reduced switch count (Dakka *et al*., 2024). To ensure DC voltage regulation and UPF operation in the utility AC voltage and current, we developed a cascaded PI controller. Additionally, the implementation of a modest inductive filter on the input line, combined with the developed controller, enables the generation of a low-harmonic AC current waveform. To address the challenge of high switching frequencies in rectifiers, we employed a multicarrier modulation technique and PWM. Control over the DC ripple is maintained using a DC-link capacitor (Safayatullah *et al*., 2022). This facilitates efficient power flow from the grid to electric vehicles. Operating with a 230 V input voltage, 400 V output battery voltage, and a 25 kHz quality resonance frequency to lowest the power rating of the V2G is 5 kW. The higher frequency allows for smaller and lighter inductors and capacitors for energy storage. The G2V battery converter in the EV exhibited a measured efficiency of 97.2%. In tackling the issue of high switching frequency, we propose a modern multi-level boost PFC rectifier circuit. This design employs a smaller number of switches although maintaining superior working standards, resulting in significantly improved power conversion efficiency. Moreover, the rectifier enhances UPF correction capabilities, ensuring compliance with global regulations. The overall system benefits from simpler, more cost-effective, and reliable rectifiers.

Table 4: *Assessment of conventional converter network topology.*

Converter topology Features	Diode rectifier	2L-B2B VSC	ZSI	Multi-level converter	Matrix Converter	Nine switch AC-AC converter
Need controlled switches	None	Less	Less	Large	Large	Least
Circuit configuration	Simple	Simple	Simple	Complex	Complex	Simple
Cost	Very low	Moderate	High	Very high	high	Low
DC-link capacitor	Yes	Yes	Yes	Yes	No	Yes
Operational stages	Two	Two	Two	Two	One	One
Waveform quality	Good	Better	Better	Best	Better	Depends
Harmonic distortion	High	Moderate	Low	Least	Low	Depends
Switches losses	None	High	High	Low	Low	High
Conduction losses	Low	Low	Low	Highest	High	Low
Reliability	High	Low	High	Low	High	Low
Bi-directional power flow	No	Yes	Yes	Yes	Yes	Yes
Control complexity	Easy	Moderate	Moderate	Most complex	More complex	complex

In study (Sivamani and Mohan, 2022) presents a novel topology for Multilevel inverters (MLIs) operating at limit power products using decreased power components. The modern MLI circuit arrangement makes the use of four DC sources as a power module with less use of switches. The MLI has limited disadvantages, for instance an increased amount of power components and voltage balancing problems. However, it has also reduced the quantity of gate drive circuits in assessment to recent topologies. The circuit needs 2 switching devices, 28 gate drive circuits as evaluated to the standard network topology. The standard topology requires a 4 switch devices and 34 gate drive circuits for 5 level output voltage (Gupta and Jain, 2013; Pavitra and Giridhar, 2015; Ruiz-Caballero *et al*., 2009). The FPGA controller delivers the continuous PWM pulses for regulating the three-phase cascaded MLIs. The proposed structure is designed for single and three phase systems to work in both symmetrical and asymmetrical arrangements. This study (Jagabar Sathik *et al*., 2020) presents a novel cascaded MLI configuration design on less power switches for the maximum number of levels. It comprises of sequence linking of VSI for higher number of output voltage level to operate in symmetric condition. Several technical parameter comparisons are done and verified for nine-level output voltage. From results it is seen that in cascaded h-bridge (CHB) inverter and neutral point clamped (NPC) inverter uses higher number of switches as much as 16 which are reduce to half in the proposed model. Furthermore, in study (Kumawat and Palwalia, 2020) gives a brief information about different types of reduced switch count multilevel inverters (RSC-MLIs) configurations, which are successfully examine for an optimization technique of hybrid genetic algorithm to solve selective harmonic elimination (SHE). This technique eliminates the larger use of capacitors, diodes, switches, and gate drive circuits to minimize the dimension and system price and thus improves the PQ of the system. Besides, in this study (Iqbal *et al*., 2021), switched-capacitor boost inverters (SCBI) with 9 level output has been proposed with reduce component count for solar PV utilization with high frequency operation.in comparison with other topologies the proposed nine-level (9L-SCBI) topology have 11 semiconductor elements, only one diode with three capacitors of source voltage equal to the input source and a voltage gain of 4 is obtained. Similarly, in this study (Sreekesh and Maiti, 2019), represents Multilevel STATCOM for Medium Voltage (MV) applications with less component count as compared to star-connected cascaded H-bridge (CHB), Delta-connected CHB, Double-star connected CHB. It comprises of three phase bridge circuit, wave-shapers, and a bidirectional switch. The purpose of the wave-shaper is to generate voltage almost near to sinusoid. Since, it simultaneously eliminates the need of PF and decreases magnetic interference. Table 5, explain the assessment of reduced switched counts inverters integrated with the APF feature applications.

In this study (Omer *et al*., 2020), presents an extensive assessment and category of reduce switch count MLI topologies. It highlights the issues of quality, design, suitability, and constraints along with the over-all components total, requirement of passive component, DC sources, high switches voltage ranking. The MLIs are in high demand for their use in average voltage

Table 5: *Assessment of RSC-APF inverters.*

Author	(Fatemi et al., 2013)	(Liu et al., 2009)	(Trinh and Lee, 2013)	(Limongiet al., 2015)	(Bhattacharya et al., 2012)	(Asiminoaei et al., 2007)	(Jacobina et al., 2003)	(Cursino et al., 2006)	(Asiminoaeiet al., 2008)
Topology	**One leg**	**Three leg**	**Two leg**	**Two leg**	**H-bridge**	**Full bridge**	**Four, Three, Five legs**	**Five leg**	**Six leg**
Modulation/control	SPWM/ EF-DF	SPWM	PI/VPI current	SPWM/PI	SPWM/PI/ FF-FB	SPWM/PI/ FF-FB	SPWM	SPWM	SPWM/PI
Capacity (kVA)	2.5	5	1.5	1.8	3 kW	15 kVA	~1.5 kVA	~1.5 kVA	5 kVA
Switching frequency (kHz)	6	3.2	10	20	550 Hz and 20 kHz	12.6 kHz	5	10	12
Conventional topology	6	12	6	9	12	12	+	12	12
Reduced switch count	3	9	4	6	8	12	8, 6, 10	10	12
No. of filter inductors	1	3	3	6	5	6	-	3	12
No. of filter capacitors	+	0	0	6	5	6	3	+	6
No. of DC capacitors (µF)	3@2200	1@2350	2@2000	1@4700	1@4700	2@4.4mF	2@1000	2@2200	1@2.2mF
THD %	60 - 1	64.74 – 1	24.4-1.89 (RL) 30.2-1.97 (RLC)	36-3 (no load) 43-5.6 (load)	4.70, 23.50	1.26, 1.11	0.8 (8 Switch), 0.6 (6 Switch)	1.54 (1st) 0.8 (2nd)	27 - 2
Estimated efficiency	High	Medium	Medium	Low	Medium	Low	High	Medium	Low
DC-link voltage (v_{dc})	200	320	420	120	26	400	100	200	250
Grid interface (Transistor)	3 VSI	6 VSI	4 VSI	3 VSI	4 VSI	6 VSI	2 VSI, 4 VSI	4 VSI	12 VSI

products (Vemuganti *et al*., 2021). Though, with their circuit complexity, price, dimension, and control difficulty they have limited value in the industrial requirement. To address the abovementioned criticality, several studies detailed explain different categories of reduce switch count MLI network topology. These studies discuss the limitations, organization, reports, and range of applications (Kubendran *et al*., 2022; Vemuganti *et al*., 2021). This study explains a low-cost multilevel modular switched capacitor DC-DC converter for hybrid compact device VSI counts in EV (Cao *et al*., 2015). To link the DC capacitor or bus to the EV batteries a bidirectional boost DC-DC converter is installed as a crossing point of the three-phase VSIs. The major issue arrives in the design of high rating power inductors, make the system converter large, heavy, costly, and beside thermal issues (Khalid *et al*., 2022). This study proposed a circuit with low device number, voltage stress and current stress. it comprises a low conduction loss, simple control, modular structure, high and soft switching frequency operation capability, in comparison with another multilevel modular switched capacitor DC-DC converter. The device number in the proposed circuits is significantly reduce to half of the flying capacitor multilevel DC-DC converter (FCMDC), and to one third in comparison with single-wing multilevel modular capacitor-clamped DC-DC converter (SW-MMCCC) specially when the conversion ratio is at the peak level. In this study (Ranjan and Dhamse, 2016), a compact VSI design in EVs has been proposed in which six switches has been reduced to four switches and three legs is reduced to two legs to generate three phase supply. The topology is made efficient by connecting two ultra-capacitors in series with the four switches. To achieve the results of a balance three phase output current, a carrier based PWM is applied in the system. This study (Nguyen *et al*., 2020), presents a novel multifunctional onboard battery charger for EVs with reduce integer of circuit modules. In this study idea, HV battery is charged when the OBC relates to the grid, the switches at the low voltage LV charging circuit becomes AC-DC converter using an active power decoupling function (APD). large capacitor banks are eliminated by small DC-Link capacitors to avoid additional switches, gate circuits or heat sink. Similarly, when the EVs is in motion (Siddique *et al*., 2020), the low voltage charging circuit functions as two inductors and a capacitor (LLC) resonant converter for charging the LV battery from the HV battery. So, by adding DC-DC converter for charging LV and HV batteries, contribute to the same transformer core and components, size and price are reduced by 52.3% and 46.9%in comparison to the standard non-isolated onboard charger (OBC) (Sayed and Massoud, 2022).

Table 6: *Assessment of the conditions of DC-DC converter topologies for electric vehicles (EVs).*

Types	Ref.	L	C	D	HFT	Sw. No	V_O V	V_{in} V	V gain (db.)	Isolation	Expected cost	Advantages	Disadvantages
Boost DC-DC converter (BC)	(Gholami *et al.*, 2024)	1	1	1	0	1	400	200	6.02	No	Low	-Meeting EMI requirements are easy -Simple circuitry -Low cost -Simple control circuity	-Large capacitor is required -High ripple rate -Parallel devices require at a high power level. -Voltage gain <4:1
Interleaved 4-Phase Boost DC-DC converter (IBC)	(Martinez-Vera and Banuelos-Sanchez, 2024)	4	1	4	0	4	400	200	6.02	No	Moderate	-Reduce input current ripples. -High voltage gain -Reduce the passive components size -Simple control	-High switching losses -Sensitive to the duty cycle change -High components count
Boost DC-DC Converter with Resonant circuit (BCRC)	(Das, 2024; Yue and Wang, 2024)	2	3	2	0	2	280	150	5.42	No	Low	-The heat sink size is reduced -Compact size -Soft switching; -Low EMI	-Low voltage gain -Not suitable for the high power conversion
Full bridge Boost DC-DC converter (FBC)	(Kim and Park, 2024)	1	1	4	1	4	400	200	6.02	No	Moderate	-High voltage step-up is possible -Efficiency is around 91.5% at full load -Reduce voltage stress on the switching circuit -Galvanic isolation	-Due to HFT additional clamping circuit is required. -High current stresses on the switching circuit -Large capacitor is required
Isolated ZVS DC-DC converters (ZVSC)	(Bharathiraja and Rubavathy, 2024)	1	4	0	1	4	300	200	3.52	Yes	Moderate	-No additional clamping circuits is required. -Reduce switching losses -Decrease EMI factor -Increase power density	-High current rating of gates -Low fault tolerance capability -Large capacitor is required
Sinusoidal Amplitude HV DC bus converter (SAHVC)	(Pottekkat *et al.*, 2024; Yahaya *et al.*, 2024)	0	3	0	1*	6	650	~650	-	Yes	High	-Mode symmetry high spectral purity -Ensures noise-free operation. -Achieves high efficiency at 1 kW/in3 -Minimized output impedance. -Flat output impedance up to 1MHz	-Complex Control technique -Complex gate switching pattern -Not suitable for the high-power conversion
Multiport isolated DC-DC converter (MPC)	(Bhattacharyya, Selvaraj, Sen, and Giri)	0	1	0	1	12	400	250,200	6.02	Yes	High	-Minimize output voltage ripples. -High voltage gain -Common ground level for all gates -Galvanic isolation from all input sources -Bidirectional power flow	-High component count -Synchronization is difficult. -Sensitive to duty cycle change at load step -Complicated analysis during transient and steady state
Multi-device Interleaved Bidirectional DC-DC converter (MDIBC).	(Amoriya *et al.*, 2024; Díaz-Bernabé *et al.*, 2024)	6	1	12	0	6	400	250,200	6.02	No	Moderate	-Efficiency up to 97% -Low current stress on switches -Capabilities of delivering the high-power value while maintaining the desired level of the output voltage -Reduce the passive component size -Reduce heat sink size -Simple control technique -Bidirectional power flow -Suitable for single port converter	-Sensitive to duty cycle change at load step -High component count -Complicated analysis during transient and steady state

*L = inductor, C = capacitor, D = diode, HFT = High frequency transformer, * = center tap transformer, Sw No = number of switches (MOSFETs/ IGBTs), Vo = output voltage, Vin = input voltage, Vol. = volume, Wgt. = weight, VGain = Voltage gain in dB.*

Table 7: *Evaluation of three-phase reduced switch count APF topologies.*

Authors	Modulation/ control	Capacity kVA/ kW	Actual topology	Reduced switches	No. of diodes	No. of filter inductors	No. of filter capacitors	No. of transmission line inductors	Grid voltage (V)	No. of DC capacitors (µF)	THD (%)
(Yeh and Manjrekar, 2007)	PWM/PI	1	8	6	0	1	0	1	120	2@-	3.54
(Choi *et al*., 2005)	SPWM	3VA	8	6	0	1	0	-	220	1@1880	3.5
(Lam*et al*., 2012)	SPWM/Adaptive DC-link	-	8	6	0	3	3	3	55	2@190	3.00
(Liu *et al*., 2009)	SPWM	5	12	9	0	3	0	3	208	1@2350	2
(Trinh and Lee, 2013)	PI/VPI current	1.5	6	4	0	3	0	3	127	2@2000	1.89, 1.97
(Limongi *et al*., 2015)	SPWM/PI	1.8	9	6	0	6	6	6	220	1@4700	3, 5.6
(Jou*et al*., 2008)	SPWM/PI	4	6	4	0	3	3	3	220	1@2200	4.96.
(Wu *et al*., 2007)	SPWM/PI	7	6	4	0	3	3	3	380	1@4700	4
(Lin and Ou, 2004)	Hysteresis	5	9	6	0	3	0	-	110	2@2200	3.6.
(Lin and Wei, 2003)	SVPWM/PI	2	12	8	4	3	0	3	110	2@2200	3.10
(Kolar*et al*., 2007)	SVPWM	6.8	18, 15	15, 9	18, 18	-	3, 3	-	400	-	-
(Vodyakho and Mi, 2009)	SV/PWM	7.5	16	12	6	4	4	-	400	1@4.4mF	6.08
(Khadkikar*et al*., 2011)	SVPWM/PQ	20	8	6	0	4	0	4	35	2@1200	4.91
(Vodyakho and Kim, 2009)	Hysteresis	15	8	6	0	4	3	-	-	2@4.4mF	6.88
(Wang *et al*., 2013)	SVPWM	50	6	4	0	3	0	-	380	2@5000	17.8
(Itoh*et al*., 2011)	SVM/SPWM/PI	1	24	12	36	3	0	-	200	8@47, 100, 220	3.40
(Bhattacharya *et al*., 2012)	SPWM/PI/FF and FB	3	12	8	0	5	5	9	110	1@4700	4.70 23.50
(Daniel and Abirami, 2013)	SPWM/PI	3.3	12	8	0	6	6	6	110	2@3300	0.03
(Asiminoaei *et al*., 2007)	SPWM/PI/FF and FB	15	12	12	0	6	6	6	300	2@4.4mF	1.26 1.11
(Heydari*et al*., 2012)	PWM	1	9	6	0	6	0	3	200	3@2200, 1100,2200	1.50
(Barrero*et al*., 2003)	DEAD-BEAT	3	-	6	0	6	3	3	110	2	2.66
(Jacobina *et al*., 2003)	PWM	~1.5	-	8, 6, 10	0	-	-	3	60	2@1000	0.8 0.6
(Cursino *et al*., 2006)	PWM	~1.5	12	10	0	3	0	-	100	2@2200	1.54 0.8
(Asiminoaei *et al*., 2008)	SPWM/PI	5	12	12	0	12	0	6	400	1@2.2mF	2
(Lam *et al*., 2014)	SPWM/Adaptive DC-link	10	8	6	0	4	3	3	200	2@3.3mF	4.5
(Ooi*et al*., 2015)	SRF-LS-PWM	1	18	12	24	3	0	-	60	4	5
(dos Santos *et al*., 2011)	SPWM/PI	3	12	10	0	3	0	-	110	2@2200	1.65
(Karanki*et al*., 2013)	PI/ HYSTERESIS	5	12	12	0	6	6	6	230	1@2200	2.80
(dos Santos*et al*., 2010)	SPWM/PI	2	10	8	0	3	3	3	100	2@2200	-
(Lin*et al*., 2003)	SVPWM/PI	2	12	8	4	3	0	3	110	2@2200	4.20
(Anand*et al*., 2014)	SVPWM/PI	10	6	6	0	3	3	3	400	1@25	5.90
(Vinod and Chandra, 2006)	SPWM/PI	1	16	14	0	6	6	-	100	1@5000	2.30

Similarly, this study gives a brief review about the latest research and ongoing trends on various multilevel inverter topologies for the new upcoming electrified transportation technology. The paper also explains about various higher DC-Link voltage advantages and disadvantages in traction inverter. A comparison review of various multi-level inverters is performed with their two-level counterpart keeping efficiency, power density, cost, reliability, PQ problems, and fault tolerance as major concern. Table 6 summarizes the assessment of the conditions of dc-dc converter topologies for EVs (Chakraborty *et al*., 2019; Poorfakhraei *et al*., 2021). All the details of reduced switch count APF topologies parameters, (Amin *et al*., 2020; Bishla and Khosla, 2024; Inci *et al*., 2024; Tareen *et al*., 2017) including L, C, D components, switch counts, and total harmonic distortion (THD) are illustrated in Table 7.

Conclusions and Recommendations

This paper offers a comprehensive review of literature regarding the progressive reduction of switches in battery charging, particularly with the APFs configuration. An effort to minimize costs by reducing the number of components in converters has been extensively explored. The study extensively categorizes conference papers, journal articles, and transaction publications, emphasizing comparisons in EV and APFs power grid applications. The primary focus is on scrutinizing EV battery chargers for innovative battery designs and topologies with reduced switch count configurations. Literature review also focused on the classification of APF topologies and the development of advanced control schemes within the area of grid-tied inverters. Also, it highlights the compilation of relevant publications related to advanced reduced switch count network topology and composite control methods for VSI systems. Furthermore, it includes a detailed comparison of modern advancements and their definite features in this field.

Novelty Statement

This paper highlights the EV battery chargers for operating a novel battery design, control schemes and topologies with reduced switch count topologies. It analysis a comprehensive and systematic review of the published work proceeding on the progressive decrease of switches for smart battery chargers with the APFs configuration.

Author's Contribution

Tayyaba Gul Tareen: Data curation, Investigation, formal analysis.
Wajahat Ullah Khan Tareen: Writing- review & editing
Muhammad Aamir: Methodology, Writing, validation
Jehanzeb Khan: Methodology, Writing, validation
Naveed Jan: Formal analysis, synthesize study data.

Conflict of interest
The authors have declared no conflict of interest.

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