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Impact of Modern Non-Linear Loads on Reactive Power Demand and Power Quality: A Comparative Review of STATCOM Topologies for Distribution Systems

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Abstract: The growing share of power-electronic-based loads on low-voltage distribution networks — electric vehicle (EV) chargers, variable frequency drives (VFDs), switched-mode power supplies (SMPS), LED lighting drivers, and data-centre infrastructure — is changing the reactive power profile that utilities must manage. Unlike conventional linear loads, these devices draw non-sinusoidal current, depress the effective power factor, and introduce harmonic distortion that static VAR compensators (SVC) and conventional capacitor banks cannot correct. The Static Synchronous Compensator (STATCOM), a voltage-source-converter-based Flexible AC Transmission System (FACTS) device, has emerged as a faster and more versatile alternative. This paper reviews how modern non-linear loads alter reactive power demand at the distribution level and comparatively surveys the principal multilevel converter/STATCOM topologies reported in the literature — two-level and multipulse configurations, neutral-point-clamped (NPC), flying capacitor (FC), cascaded H-bridge (CHB), modular multilevel converter (MMC), and hybrid arrangements — evaluating them against switch count, harmonic performance, control complexity, and suitability for distribution-level deployment. The review finds that while CHB and MMC topologies dominate high-power transmission-level STATCOM applications, reduced-switch-count and hybrid-clamped variants remain the more practical direction for low-voltage, distribution-connected compensators addressing modern residential and light-industrial non-linear loads. Gaps in the existing literature specific to EV-charging-dominated low-voltage feeders are identified as a direction for future work.

Index Terms: Electric vehicle charging, FACTS, Multilevel inverter, Non-linear loads, Power quality, Reactive power compensation, STATCOM

1 INTRODUCTION

Reactive power management has historically been treated as a slowly varying, largely predictable problem, addressed with fixed or switched capacitor banks sized against aggregate industrial and residential load. This assumption is weakening. Power-electronic interfaces — rectifiers, inverters, and switch-mode

converters — increasingly stand between the grid and the end load, and each of these interfaces draws current that departs from the sinusoidal, in-phase ideal that the older compensation philosophy assumed.

Electric vehicle charging is the most visible example. Field and laboratory measurements report EV charger power factors as low as 0.4–0.6 when uncompensated, together with measurable voltage unbalance and current total harmonic distortion (THD) that rises sharply during active charging [1]–[4]. Non-linear loads more broadly — VFDs, SMPS-based consumer electronics, LED drivers, and data-centre power supplies — have grown from an estimated 15–20% of total utility load in the 1990s toward a majority share of connected load today.

This shift matters because conventional reactive-power compensators were not designed for it. Thyristor-switched capacitors and SVCs respond on a cycle-by-cycle basis and struggle with the harmonic content and the rapid, intermittent switching pattern typical of EV chargers and other power-electronic loads. The Static Synchronous Compensator (STATCOM) — a voltage-source-converter-based device that synthesises a controllable AC voltage rather than switching passive elements — offers continuous, fast reactive power control largely independent of system voltage, and is increasingly proposed at the distribution level for exactly this reason [5]–[8].

This paper has two aims. First, to summarise, from existing literature, how modern non-linear loads specifically alter reactive power demand and power quality at the distribution level. Second, to comparatively review the STATCOM/multilevel converter topologies available to address that demand, so that the topology choice can be matched to the load profile rather than adopted by default.

2 Modern Non-Linear Loads and Their Effect on Reactive Power Demand

2.1 Electric Vehicle Charging Loads

EV chargers are rectifier-front-end loads and are inherently non-linear. Multiple field studies report current THD rising into the 15–20% range during active charging, together with measurable phase current imbalance where single-phase charging dominates a feeder [1]. Reported power factors for uncompensated EV charging equipment range from approximately 0.4 to 0.6 lagging, meaning a substantial reactive component is drawn for every kW of real charging power delivered [4]. A recent multi-vehicle measurement study characterised harmonic behaviour across several current-generation EV models under slow and fast AC charging modes, confirming that harmonic signatures vary meaningfully by vehicle and charging power level rather than following one fixed profile [3].

2.2 Other Power-Electronic-Interfaced Loads

Variable frequency drives, uncontrolled rectifier-based SMPS in consumer electronics, and LED lighting drivers present a similar — though individually smaller — non-linear burden. Their cumulative effect on a feeder is significant because of high penetration density rather than any single device's rating. Data-centre loads add a further, growing contribution through their UPS and rectifier front ends [reference required — this claim needs a specific, verifiable citation before inclusion in the final manuscript].

2.3 Consequences for Distribution Networks

The composite effect reported in recent reviews includes voltage instability, thermal stress on distribution transformers, and elevated peak reactive demand that older network planning assumptions did not anticipate [2]. Reviews of large-scale EV integration further note that these effects are strongly dependent on charging coincidence (how many chargers operate simultaneously) and network topology, which complicates any single compensation strategy [2], [4].

3 STATCOM: Operating Principle

A STATCOM is a shunt-connected voltage-source converter that exchanges reactive power with the grid by controlling the magnitude and phase of its output voltage relative to the line voltage. For a STATCOM voltage E_S connected through a coupling inductance of reactance X to a line voltage E_L with power angle δ, the active and reactive power exchanged are commonly expressed as:

$$P = (E_S \cdot E_L / X) \sin \delta \quad (1)$$

$$Q = (E_S^2 - E_S \cdot E_L \cos \delta) / X \quad (2)$$

where E_S and E_L are in volts, X is in ohms, δ is the power angle in radians, and P and Q are in watts and VAR respectively [as presented in the source conference paper reviewed for this study; verify against a primary STATCOM control-theory reference before final submission]. In steady-state operation, δ is adjusted to control active power exchange (needed only to cover converter losses in a pure reactive-compensation role), while the modulation index — and hence E_S — is adjusted to control reactive power output. A STATCOM operating with no active power source behind its DC link (E_S set purely by capacitor voltage) delivers reactive power only, which is the mode relevant to distribution-level power-factor correction.

4 Classification of STATCOM / Multilevel Converter Topologies

The power-electronic realisation of the STATCOM has evolved from simple two-level voltage-source converters toward multilevel structures that reduce per-device voltage stress, lower switching frequency, and improve harmonic performance. The principal families reported in the literature are summarised below.

4.1 Two-Level and Multipulse Configurations

The conventional two-level VSC-STATCOM is the simplest realisation and remains a useful performance baseline. Multipulse configurations (6-pulse, 12-pulse), which combine several two-level bridges through zigzag transformer arrangements, were an early approach to improving harmonic performance without multilevel switching, though at the cost of bulky magnetics and reduced flexibility [6], [9].

4.2 Neutral-Point-Clamped (Diode-Clamped) Topology

The NPC (diode-clamped) topology splits the DC bus into equal voltage steps using clamping diodes, producing a stepped output waveform with fewer harmonics than a two-level converter for the same switching frequency. This is the topology used in the single-phase 5-level D-STATCOM design reviewed as the starting point for this study [9]; for an n-level configuration, diode reverse-voltage stress scales as E/(n−1), meaning that increasing the level count reduces voltage stress per component at the expense of additional clamping diodes [9].

4.3 Flying-Capacitor (Capacitor-Clamped) Topology

The flying-capacitor topology replaces clamping diodes with capacitors, offering redundancy in switching states useful for capacitor voltage balancing, though at the cost of a larger number of bulky, precisely-rated capacitors as level count increases [7], [8].

4.4 Cascaded H-Bridge (CHB)

The CHB topology connects multiple H-bridge cells in series, each with its own isolated DC source, to synthesise a stepped AC waveform. Several comparative reviews report CHB as delivering the best harmonic performance among common multilevel topologies for STATCOM duty, and it is considered particularly well suited to high-power applications because of its modularity, though the requirement for

multiple isolated DC sources is a practical constraint at lower power levels [7], [8].

4.5 Modular Multilevel Converter (MMC)

The MMC family — including single-star, single-delta, double-star bridge-cell, and double-star chopper-cell variants — has become the preferred topology for high-voltage, high-power STATCOM installations in recent literature, owing to its scalability, fault tolerance, and reduced filtering requirement. It is more commonly reported at transmission level than at distribution level [8].

4.6 Hybrid and Reduced-Switch-Count Topologies

Hybrid arrangements — combining, for example, a fundamental-frequency high-voltage H-bridge stage with a high-frequency low-voltage stage — and reduced-switch-count topologies (T-type, packed U-cell) aim to retain multilevel harmonic performance while reducing component count and cost, which is directly relevant to distribution-level, cost-sensitive deployments such as the single-phase residential/light-industrial context this review is concerned with [8], [9].

5 Comparative Summary

Table 1 summarises the qualitative trade-offs reported across the reviewed literature, comparing each topology family by relative switch count, DC-source requirement, harmonic performance, typical application level, and key limitation. Values are descriptive (relative) rather than numeric, since no simulation or hardware testing was performed as part of this review; a follow-up study with matched simulation conditions would be required to produce comparable quantitative THD and efficiency figures.

Table 1. Qualitative comparison of STATCOM/multilevel converter topologies

Topology	Relative switch count	DC source requirement	Typical harmonic performance	Typical application level	Key limitation
Two-level VSC	Low	Single	Poor (needs large filter)	Low power / baseline	High THD, large filter
Multipulse (6-/12-pulse)	Moderate	Single (via transformer)	Moderate	Medium voltage	Bulky zigzag transformers
NPC (diode-clamped)	Moderate–High	Single, split levels	Good, improves with levels	Medium voltage	Diode count grows with levels
Flying capacitor	Moderate–High	Single, split levels	Good	Medium voltage	Bulky, many capacitors
Cascaded H-Bridge (CHB)	High	Multiple isolated	Best among common topologies	High power	Needs isolated DC sources
MMC	Very high	Multiple (modular)	Very good, low filtering need	High voltage transmission /	Complex balancing control
Hybrid / reduced-switch-count	Reduced by design	Mixed	Good, topology-dependent	Distribution / cost-sensitive	Design/control complexity trade-off

6 Research Gap and Future Scope

Across the reviewed literature, STATCOM topology comparisons are predominantly framed around transmission- and medium-voltage applications, or around generic industrial harmonic loads. Comparatively little published work evaluates topology choice specifically against the load signature of EV-charging-dominated, single-phase, low-voltage residential feeders of the kind increasingly common in Indian distribution networks. This is the gap this review positions as a direction for further work: matching a specific reduced-switch-count or hybrid-clamped multilevel STATCOM design against a realistic EV/residential non-linear load profile at distribution voltage, ideally validated through MATLAB/Simulink simulation rather than qualitative comparison alone.

7 Conclusion

Modern non-linear loads — EV chargers foremost among them — are measurably changing the reactive power and harmonic burden that distribution networks must absorb, in ways that conventional compensation was not designed around. STATCOM technology, in its various multilevel realisations, offers a faster and more flexible response than switched capacitor banks or SVCs. Among the topologies reviewed, CHB and MMC dominate high-power applications on harmonic performance, while NPC, flying-capacitor, and hybrid/reduced-switch-count designs remain the more practical candidates for the cost- and complexity-constrained distribution level where EV charging load is actually concentrated. This qualitative review is intended as a foundation for a follow-up simulation-based study matching topology choice to a specific, real distribution feeder load profile.

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