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MODERN METHODS OF REACTIVE POWER COMPENSATION: A LITERATURE REVIEW AND COMPARISON WITH TRADITIONAL APPROACHES

Аннотация. This article reviews the development of reactive power compensation from traditional capacitor banks and reactors to converter-based and intelligent solutions. The reviewed literature is divided into two groups: baseline studies published up to 2017 and recent studies published after 2023. The comparison covers operating principle, response speed, harmonic performance, voltage support, control complexity and cost. Traditional capacitor banks remain the most economical choice for steady and predictable inductive loads, but their discrete response and possible resonance limit their use in strongly distorted networks. SVC, STATCOM, DSTATCOM, active power filters and UPQC provide faster and more flexible compensation. Recent research also combines these devices with smart inverters, soft open points and data-driven control. The review shows that no single device is best for every network. A coordinated hybrid solution is usually preferable when load variation, harmonics and renewable generation occur at the same time.

Ключевые слова: Reactive power compensation, capacitor bank, SVC, STATCOM, DSTATCOM, active power filter, UPQC, power quality, Volt-VAR control.

1. Introduction

Reactive power is necessary for creating magnetic and electric fields in motors, transformers, cables and other alternating-current equipment. It does not produce useful mechanical work, but it increases line current when it is supplied over a long distance, causing losses and voltage drop. Compensation therefore supplies or absorbs it close to the point of need. The task is more difficult in networks with renewables, electronic converters and nonlinear loads, because power changes quickly and harmonics may interact with capacitors. This qualitative review compares publications from 2014–2017 with studies from 2024–2026 to explain the change from conventional equipment to coordinated, converter-based control.

2. Basic Principle of Compensation

For a sinusoidal system, apparent power S consists of active power P and reactive power Q. The power factor is $PF = \cos\varphi = P/S$, where $S = \sqrt{(P^2 + Q^2)}$. When an inductive load takes positive reactive power, a shunt capacitor supplies part of that demand locally. The required capacitor rating for power-factor correction can be estimated by $Q_c = P(\tan\varphi_1 - \tan\varphi_2)$, where φ1 is the initial angle and φ2 is the desired angle. A smaller reactive component reduces current, I^2R losses and voltage drop. However, excessive compensation may cause a leading power factor or overvoltage. Capacitors can also resonate with network inductance. Slowly changing loads can be served by switched steps, whereas rapid voltage changes require continuous electronic control.

3. Traditional Compensation Methods

Shunt capacitor banks are the most common traditional solution. They are simple, efficient and inexpensive, and they release feeder capacity by supplying inductive reactive power near the load. Murty and Kumar showed that capacitor size and location should consider loading level, unbalance and realistic load models [1]. A recent study by Blasco et al. confirms that properly selected single-phase capacitors can still be an economical way to reduce line losses in unbalanced low-voltage systems [2]. Shunt reactors absorb capacitive reactive power on lightly loaded lines, while synchronous condensers give continuous support but have higher losses and maintenance. Passive LC filters compensate selected harmonics, although network changes can detune them. Pană and Băloi show why harmonic impedance should be evaluated before passive compensation is added [3]. Traditional methods are best when load patterns are known, distortion is limited and low life-cycle cost is the main criterion.

4. Modern Power-Electronic Methods

The static VAR compensator (SVC) uses thyristor-controlled reactors and switched capacitors to change reactive power much faster than mechanical switching. The STATCOM uses a voltage-source converter and can inject or absorb reactive current almost continuously. It normally gives stronger support during depressed voltage. A direct comparison of SVC and STATCOM reported a small overall advantage for STATCOM in dynamic performance [4].

At distribution level the same principle is applied in a DSTATCOM. Its controller maintains the point-of-common-coupling voltage and may correct unbalance. Optimized PI settings improved DSTATCOM response in an earlier study [5]. Recent work compares zero-sequence controllers under unbalance [6] and studies STATCOM stability in weak grids [7]. Thus, control design and grid strength must be considered together.

An active power filter (APF) measures unwanted current components and injects an opposite compensating current. It can correct reactive current and several harmonics without the fixed tuning of a passive filter. In experimental tests, a genetic-algorithm-tuned shunt APF reduced current THD from 20.2% to 4.2% for an R-L load and from 56.1% to 4.5% for an R-C load, with power factor close to unity [8]. A unified power quality conditioner (UPQC) combines shunt and series converters, correcting both load current and supply-voltage problems. This wider function suits sensitive loads, but cost and control complexity are higher.

Hybrid compensation combines a low-cost passive or capacitor part with a smaller active converter. Auto-tuned hybrid filters avoid fixed overcompensation at light load [9]. More recently, simultaneous allocation of capacitors and APFs was found to be more cost-effective than sequential planning in a distorted distribution network [10]. Wide-bandgap semiconductors offer another improvement: a hybrid IGBT/SiC T-STATCOM study reported reductions of up to 50% in total losses and component costs compared with the evaluated state-of-the-art designs [8].

5. Intelligent and Coordinated Control

Table 1 summarizes the main engineering trade-offs. Response time is only one criterion. The designer should also evaluate harmonic distortion, voltage unbalance, grid strength, expected load variation, converter losses, maintenance skill and total life-cycle cost.

Table 1

Comparison of reactive power compensation approaches

Method	**Response and capability**	**Main advantages**	**Limitations / best use**
Capacitor bank / passive filter	Stepwise; steady reactive power and selected harmonics	Lowest cost, low losses, simple operation	Resonance and overcompensation risk; best for stable loads
SVC	Fast thyristor control; continuous within its range	Mature high-power technology; good voltage regulation	Large filters and weaker low-voltage output than STATCOM
STATCOM / DSTATCOM	Very fast bidirectional reactive current	Strong dynamic voltage support; handles unbalance	Higher investment and control sensitivity; variable loads
APF / UPQC	Fast compensation of harmonics, reactive current and voltage events	Broad power-quality improvement	High converter rating and complexity; nonlinear or sensitive loads
PV inverter / soft open point	Fast distributed Volt-VAR control	Uses existing converter capacity; supports renewable hosting	Capacity varies with active power; needs coordination

A practical rule is to match the device to the disturbance. A stable industrial load with moderate harmonics usually needs a correctly sized capacitor bank, possibly with a detuned reactor. Rapid demand or weak voltage requires SVC or STATCOM support. Nonlinear loads need an APF or UPQC when passive filtering is insufficient. High-photovoltaic networks benefit from coordinated inverter control, but local dynamic support may still be needed during faults. Hybrid planning is therefore often more reasonable than replacing every traditional device.

6. Comparison and Practical Selection

The recent trend is to coordinate slow mechanical devices with fast electronic resources. Capacitor banks and tap changers can set an economical hourly operating point, while STATCOMs, soft open points and photovoltaic inverters make continuous corrections. Deep reinforcement learning has been used for real-time optimization with a soft open point [9], while transfer learning can reuse knowledge across operating scenarios [9,10]. Transformer-based learning with synthetic data is a new approach to distributed Volt-VAR control [10]. These methods can adapt to uncertainty, but they depend on training data and reward design. Learned policies must remain inside voltage, current and converter limits and be supervised by deterministic protection.

Conclusion

Traditional and modern reactive power compensators are not direct substitutes in all cases. Capacitor banks remain attractive because they are economical, simple and efficient for steady demand, but their weaknesses are discrete control and resonance. SVC and STATCOM provide faster voltage support; DSTATCOM, APF and UPQC also address unbalance and harmonics. Smart inverters and learning-based control increase flexibility but require careful stability and safety validation. For most modern distribution networks, a coordinated hybrid system is the best engineering compromise: conventional devices supply economical base compensation, while electronic devices handle fast and nonlinear changes

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