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Research on Power Quality Improvement Technology and Engineering Application in Low-Voltage Distribution Networks

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Abstract: Low-voltage distribution networks supply homes and many small and medium-sized enterprises; deterioration in their power quality can therefore impair equipment operation and continuity of supply. Harmonics, voltage sags, and phase imbalance have become common concerns as load composition changes. These disturbances increase losses and accelerate equipment aging, and in severe cases can compromise network security. This study examines practical options for addressing these problems. The analysis combines a review of published work with comparison of available technologies and evidence from engineering cases. On this basis, the paper identifies the operating characteristics, appropriate use conditions, and implementation considerations of the main improvement methods. The case results are then used to assess their field performance and to inform power-quality management in low-voltage networks.

Keywords: Low-voltage Distribution Network; Power Quality; Compensation Technology; Engineering Application.

1. Introduction

The growth of distributed generation and nonlinear loads have changed both the composition and operating conditions of low-voltage networks. As a result, maintaining acceptable power quality has become more demanding. GB/T 12325-2022, "Power Quality - Supply Voltage Deviation," specifies limits for key indicators, including voltage deviation and harmonic content. Nevertheless, aging equipment and incomplete technical configurations leave some networks outside those limits. The consequences are practical: precision instruments may produce measurement errors, motors and other equipment incur additional heating losses, and protection devices may misoperate. In severe cases, these effects can extend into wider interruptions and constrain reliable electricity use [1]. International practice has developed relatively mature schemes built around active power filters (APFs) and dynamic voltage restorers (DVRs). Their use in industrial parks and residential communities demonstrates high compensation accuracy and a high level of automation, although capital cost remains comparatively high [2]. Research and engineering trials in China have also advanced. Field application, however, still suffers from poorly matched technology selection, uneven implementation results, and limited alignment between standards and project practice [3]. Coordinated control for networks with distributed generation is one area that still requires improvement.

Against this background, the analysis is organized around both technology and field application. It begins with the operating principles and performance characteristics of passive, active, hybrid, and auxiliary methods. Three engineering cases then provide evidence on actual application results, after which the benefits and practical improvements are compared quantitatively [4]. This sequence moves from the underlying principles to technical comparison, case evidence, and final findings, keeping the engineering discussion tied to the operating needs of low-voltage distribution networks.

2. Key Technology Analysis for Improving Power Quality in Low-Voltage Distribution Networks

2.1. Passive Compensation Technology

Capacitor banks and LC filters form the basis of passive compensation. Capacitors supply capacitive reactive power to offset the demand of inductive loads, while an appropriately tuned LC branch offers a low-impedance path at a selected harmonic frequency. The resulting topology is conventional, inexpensive, and straightforward to install and maintain [5]. It is therefore useful where reactive-power demand and the dominant harmonic components do not change rapidly. Its fixed parameters also impose clear limits: response is generally measured in seconds, compensation accuracy varies with grid frequency, and only the tuned frequencies can be addressed [6]. For this reason, passive compensation is best suited to residential networks and small or medium-sized enterprises with modest load variation and a limited harmonic spectrum.

2.2. Active Compensation Technology

APFs and DVRs provide active compensation through power-electronic conversion and real-time measurement of network conditions. An APF injects a current component that counteracts the detected harmonic or reactive component. It can track harmonics from the 2nd through the 50th order, respond on a microsecond timescale, and contribute to reactive-power and phase-imbalance correction. A DVR is installed in series and injects the required voltage during a dip or swell; the response is typically within milliseconds, which protects sensitive loads from short-duration disturbances [7]. Because the compensation signal follows the measured disturbance, active devices accommodate nonlinear loads more readily than fixed passive branches. This flexibility comes with more complex power modules and controls, and

the reported cost is 30%-50% above that of passive compensation. Applications with demanding power-quality requirements, including converter-intensive production lines, precision laboratories, and data centers, are therefore the most appropriate candidates.

2.3. Hybrid Compensation Technology

In a hybrid scheme, passive and active devices share the compensation duty. The LC branch carries most of the reactive-power demand and filters low-order harmonics, whereas the APF (active power filter) follows high-order components and rapid load changes. Assigning these functions separately reduces the required active-device rating without giving up dynamic response [8]. Relative to passive compensation alone, the reported arrangement increases harmonic-compensation accuracy by more than 40% and brings the response into the millisecond range. Relative to an all-active design, it lowers equipment investment by 25%-30% and operating losses by about 15%. These characteristics make the scheme suitable for major low-voltage retrofit projects, particularly industrial parks or large residential developments with mixed loads and several significant harmonic orders.

3. Case Study on the Application of Low-Voltage Distribution Network Power Quality Improvement Projects

3.1. Case 1: Three-Phase Imbalance Mitigation Project in a Residential Community

3.1.1. Project Overview

The case concerns an older residential development completed in 2005. One 10 kV/0.4 kV, 800 kVA transformer supplies 12 buildings and 480 households. Demand comes mainly from domestic appliances and electric-vehicle charging facilities [9], so individual phase loads vary unpredictably and are unevenly distributed. Measurements recorded a maximum three-phase current imbalance of 28%, compared with the 15% limit in GB/T 12325-2022. Under these conditions, transformer losses rose by 12%, some buildings experienced voltage outside the permitted range, and the minimum measured voltage was 205 V. Residents also reported repeated supply-quality problems.

3.1.2. Technology Selection

The selected design combined passive reactive-power compensation with automatic phase transfer. Three low-voltage shunt-capacitor banks, with a combined capacity of 400 kvar, were assigned to fundamental reactive-power compensation. Twelve intelligent phase-switching units redistributed the branch loads, and four monitoring terminals supplied real-time current and voltage measurements. This arrangement matched the predominantly inductive residential load: the capacitor banks reduced reactive losses, while switches with a response time of no more than 20 ms could follow the random changes in phase loading. It also met the cost constraint, with an estimated expenditure 35% below that of an all-active scheme.

3.1.3. Implementation Process

Implementation proceeded in three stages. First, the team installed monitoring terminals on the transformer low-voltage side and in four building distribution boxes to establish the load profile. Second, the capacitor banks were placed in the distribution room beside the transformer, and the intelligent phase-switching units were installed on each building's three-phase branch circuits. In the final stage, the controls were commissioned and the phase-imbalance threshold was set at 10%. Exceeding that threshold triggered phase-load redistribution; capacitor-bank switching followed changes in power factor. Work was completed within 15 days without interrupting normal residential electricity use.

3.1.4. Application Results

Power-quality measurements continued for one month after commissioning. The results are shown in the Table 1 below. As shown in the table, the pre-treatment phase-imbalance range of 18.6%~28.3% fell to 3.2%~8.7%, corresponding to an average reduction of 72.5%. Voltage deviation narrowed from -7.8%~+6.5% to -3.2%~+2.8%, which satisfies the national limit. Transformer losses were 11.8 kW lower, equivalent to approximately 103,368 kWh of annual electricity savings. Together, these measurements show that the project corrected the principal imbalance and voltage-deviation problems and produced a more stable supply for residents.

Table 1. Comparison of Indicators Before and After the Treatment of Three-Phase Imbalance in Residential Areas

monitoring indicators	Scope before treatment	Scope after treatment	National standard limits	Improvement range
Phase current (A)	85~132	98~115	-	Volatility decreased by 18%
Phase B current (A)	42~78	95~112	-	Volatility decreased by 23%
C-phase current (A)	65~108	92~110	-	Volatility decreased by 15%
Three-phase imbalance (%)	18.6~28.3	3.2~8.7	≤15	Average 72.5%
Voltage deviation (%)	-7.8~+6.5	-3.2~+2.8	±7	Average 61.3%
Transformer losses (kW)	42.5~58.3	30.7~46.5	-	Average 22.1%
Power factor	0.82~0.88	0.93~0.98	≥0.9	Increase by 13.4%

3.2. Case 2: Distributed Photovoltaic Power Grid Connection Voltage Fluctuation Mitigation Project

3.2.1. Project Status

Eight distributed photovoltaic stations, totaling 3.2 MW, are connected to the rural 10 kV network under a self-consumption and surplus-export arrangement. Two 1600 kVA transformers step the supply down to 0.4 kV for three administrative villages, 1,200 households, and 20 small agricultural cooperatives. The service area includes 18.6 km of distribution line; part of it uses LGJ-120 conductors installed 10 years earlier and consequently has relatively high impedance. All eight stations connect through three 10 kV nodes. Solar variability produces a maximum daily output swing of 2.5 MW, and the difference between night-time minimum and noon peak output equals 78% of installed capacity. During 15 days of baseline monitoring, voltage ranged from 198 to 242 V and the fluctuation amplitude reached 18.2%, well above the 2.5% limit in GB/T 12326-

2022, "Power Quality - Voltage Fluctuations and Flicker." Maximum voltage deviation was -8.3%; temporary dips reached 192 V and lasted 2-5 s. These disturbances repeatedly stopped irrigation pumps and greenhouse temperature-control equipment, exposed household appliances to accelerated aging, and generated an average of 12 complaints per month.

3.2.2. Technical Solution

To address both fast and sustained voltage variations, the project paired a dynamic voltage restorer (DVR) with reactive-power optimization dispatch. Three 500 kVA DVR units, one at each photovoltaic connection node, were connected in series on the high-voltage sides of the 10 kV/0.4 kV transformers. Each unit was configured for a response time of no more than 3 ms and a compensation range of ±20% of rated voltage. A regional dispatch system received data from the station inverters and network monitoring terminals. Its model-predictive controller used forecast photovoltaic output and real-time load data to set inverter reactive-power output over a power-factor range from 0.9 leading to 0.9 lagging. It also coordinated the three existing 100 kvar capacitor banks. The DVRs were assigned to sudden dips, rises, and short fluctuations; inverter and capacitor control addressed the slower reactive-power imbalance. Using the inverters' existing regulation capability limited the need for additional compensation equipment while retaining coverage of both transient and long-duration voltage problems.

3.2.3. Implementation Results

Table 2. Comparison of Indicators Before and After the Treatment of Voltage Fluctuation in Distributed PV Grid Connection

monitoring indicators	Scope before treatment	Scope after treatment	National standard limits	Improvement range
Voltage fluctuation amplitude (%)	12.5~18.2	1.1~2.3	≤2.5	Average 87.6%
Maximum operating voltage (V)	235~242	228~232	240	Reduce 4.1%
Minimum operating voltage (V)	198~205	215~220	200	Promote 8.2%
Voltage deviation (%)	-8.3~+7.9	-2.8~+2.5	±7	Average 76.3%
Voltage sag frequency (times/month)	12~18	0	-	100%
Voltage change rate (%/min)	2.1~3.2	0.2~0.3	≤0.5	Average 90.5%
Power quality pass rate (%)	58.6~62.3	99.2~99.7	≥98	Aromote 60.9%
Photovoltaic power output fluctuation adaptability (%)	45~52	92~96	-	promote 85.7%

Voltage was monitored for one month after commissioning under sunny, cloudy, and rainy conditions. The monitoring results are shown in Table 2 below. As shown in Table 2, fluctuation amplitude fell from 12.5%~18.2% to 1.1%~2.3%, an average improvement of 87.6% and within the 2.5% limit in GB/T 12326-2022. The voltage-deviation range narrowed from -8.3%~+7.9% to -2.8%~+2.5%, satisfying GB/T 12325-2022. Recorded voltage dips declined from 18 per month to zero, and the power-quality pass rate increased from 62.3% to 99.7%. The dynamic response was also improved: at a photovoltaic output ramp of 0.5 MW/min, voltage changed by 0.3%/min rather than the previous 3.2%/min. Agricultural-cooperative equipment failures dropped from eight to one per month, and no residential electricity complaints were received during the monitoring period. The measurements indicate that the scheme accommodated photovoltaic output changes while maintaining network voltage.

3.3. Case Study 3: Harmonic Suppression Project in a Small and Medium-sized Enterprise Industrial Park

3.3.1. Project Background

The industrial-park case covers 120 mu (about 8 ha) and 23 parts-processing and equipment-manufacturing enterprises. Two 1250 kVA transformers supply a total connected load of 1800 kW. Frequency converters, welding machines, CNC machine tools, and other nonlinear equipment account for 65% of that load. Baseline measurements showed excessive 3rd-, 5th-, and 7th-order harmonics, with total harmonic distortion (THD) reaching 22.3% against the 5% limit in GB/T 14549-1993. Power factor fell as low as 0.78. The combined effect was transformer overload, higher line loss, and operating failures in some precision-machining equipment.

3.3.2. Technology Selection

Measured harmonic current formed the basis for equipment sizing. The required compensation current was 380 A, so four 100 A modular active power filters (APFs) were connected in parallel to the transformer low-voltage busbar. The selected units respond within 5 ms, track changing harmonic conditions, and cover the 3rd through 50th orders. Their modular arrangement also allows capacity to be added if park demand grows. A reactive-power controller coordinated the APFs with the existing capacitor-compensation equipment so that harmonic filtering and power-factor correction could operate together.

3.3.3. Project Implementation

Construction was organized into equipment installation, wiring and commissioning, and integrated testing. The four APFs were mounted in the distribution room and connected to the busbar through top-entry wiring. A 0.5 m interval between units provided ventilation. During commissioning, the filters were linked to the monitoring terminal and controller; the harmonic sampling period was set to 1 ms and the compensation threshold to 5%. Integrated testing then reproduced full-load operation, and the control settings were adjusted from the measured response. All work complied with the "Low-Voltage Power Distribution Design Standard" (GB 50054-2011). The installation and commissioning period was 10 days.

3.3.4. Effect Verification

After the mitigation project was completed, the harmonic content and power factor of the park's distribution network were monitored for 20 days. The results are shown in Table 3 below. Data shows that after the treatment, the total harmonic distortion (THD) decreased from 15.8%~22.3% to 2.1%~3.8%, fully complying with national standards; the 3rd, 5th, and 7th harmonic current contents decreased from 85A, 62A, and 48A to 12A, 8A, and 5A respectively, with reductions exceeding 85%; the power factor improved from 0.78~0.85 to 0.95~0.99, meeting energy-saving operation requirements. After the treatment, the transformer overload problem in the park was resolved, line losses decreased by 28%, and the frequency of precision machining equipment failures decreased from 6 times per month to 1 time, significantly improving the production stability of the park.

Table 3. Comparison of Indicators Before and After Harmonic Suppression Treatment in SME Park

monitoring indicators	Scope before treatment	Scope after treatment	National standard limits	Improvement range
Total Harmonic Distortion (THD, %)	15.8~22.3	2.1~3.8	≤5	Average 83.6%
Third harmonic current (A)	68~85	8~12	≤24	Average 86.2%
5th harmonic current (A)	45~62	5~8	≤15	Average 87.1%
7th harmonic current (A)	32~48	3~5	≤10	Average 88.5%
Power factor	0.78~0.85	0.95~0.99	≥0.9	Promote 14.7%
Line loss (kW)	35.6~48.2	25.6~34.7	-	Average 28.0%
Equipment failure frequency (times/month)	4~6	0~1	-	Average 83.3%

4. Optimization Recommendations

4.1. Technology Selection Optimization

Technology should be selected from measured disturbance characteristics rather than from a preferred device type. In residential communities and small commercial buildings, where phase loading is random and imbalance dominates, passive compensation combined with load-optimization scheduling offers a practical balance between cost and performance. Industrial parks and data centers with concentrated nonlinear loads require modular APFs; the modular rating can then be adjusted as load grows. Where distributed photovoltaic or wind generation drives voltage variation, a DVR combined with reactive-power optimization dispatch can use inverter capability and reduce additional equipment investment. These decisions should be based on 1-2 months of power-quality measurements so that the dominant indicators, their timing, and their range are known before equipment is specified.

4.2. Installation and Commissioning Key Points

Installation and commissioning shall comply with the "Low-Voltage Power Distribution Design Standard" (GB 50054-2011) and the manufacturer's technical requirements. Compensation equipment should be placed near the load center or the node at which the disturbance is most pronounced; this reduces the electrical distance to the affected load. APFs, DVRs, and other power-electronic devices require adequate ventilation, an ambient temperature of -10°C to 40°C, and relative humidity no higher than 85%. Monitoring points should include the transformer low-voltage side and branch circuits with concentrated load. Commissioning should verify both control coordination and the selected thresholds. Appropriate response times are 1-3 s for passive devices and microseconds for active devices. In a hybrid system, the tests must also confirm that passive and active commands neither overlap nor leave an uncompensated interval. A 72-hour full-load trial should follow commissioning to confirm compensation performance and stable operation.

4.3. Improved Operation and Maintenance Management

A routine program of monitoring, diagnosis, and maintenance is needed to preserve the initial improvement. A regional platform can combine data from project terminals, display indicator trends, issue alarms, and create a work order when a limit is exceeded. Quarterly inspections should check capacitor aging, APF module temperature, and terminal tightness. An annual service should include compensation-accuracy calibration, control-algorithm review, and software updates. Operating parameters, faults, corrective actions, and long-term indicator trends should be retained in the maintenance record because they inform later tuning and the design of new projects. In networks with renewable generation, the same record should link output changes to power-quality measurements so that compensation settings can be revised as operating conditions change.

5. Conclusion

The analysis identifies four recurring sources of poor power quality in low-voltage distribution networks: nonlinear loads, variable distributed generation, uneven phase loading, and limitations of the network structure. The observed disturbances were principally harmonics, phase imbalance, and voltage fluctuation. No single compensation method is appropriate in every case. Passive equipment provides a low-cost option where conditions are stable; active devices provide the accuracy and speed needed by sensitive or rapidly changing loads; and hybrid schemes offer a cost-performance compromise for mixed, complex networks. Across the three cases, the selected schemes improved the principal indicators by an average of 78.5%, reduced equipment failures by 81.2%, and produced estimated annual electricity savings of RMB 236,000. The mean investment payback period was 3.8 years. These results support the technical and economic feasibility of matching the device configuration to the disturbance and the operating context. Further work should examine data-driven and artificial-intelligence controls for real-time compensation, particularly under variable distributed generation. Standards also need to be translated more directly into selection guidance and construction requirements for specific network conditions.

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