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Power quality enhancement and engineering application with high permeability distributed photovoltaic access to low-voltage distribution networks in Australia

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Abstract

Considering power quality problems such as overvoltage and three-phase unbalance caused by high permeability distributed photovoltaic access in low-voltage distribution networks, this paper proposes a comprehensive control scheme using a static var. generator (SVG), electric energy storage (EES), a phase switching device (PSD) and an intelligent terminal controller. The control strategies of transformer overload, bus over/under voltage, anti-countercurrent, storage battery state of charge (SOC) maintenance, and three-phase unbalance are studied. The engineering application in the Greenvale low-voltage distribution networks in Australia with high permeability distributed photovoltaics is discussed. The results show that the intelligent terminal controller is able to improve the power quality of low-voltage distribution networks through coordination with EES, SVG and PSD.

Keywords: Power quality enhancement, Engineering application, Low-voltage distribution networks, High-permeability distributed photovoltaic

1 Introduction

New energy power generation is characterized by volatility, intermittency and uncertainty. A large amount of new energy power generation has been connected to power grid through power electronic converters, resulting in increased power quality problems. These not only threaten the safe and economic operation of the power grid, but also affect the normal operation of power equipment [1–6]. A lot of research has been carried out on distributed photovoltaic access, power quality problem analysis and governance [7–11]. Reference [12] presents a coordinated control method of distributed energy storage systems for voltage regulation in a distribution network. A control strategy is proposed in [13] to enable the PVs to operate

as a synchronous generator with variable inertia using an energy storage system to deal with the problems caused by high PV penetration in power systems.

This paper focuses on the problems of voltage over-limit, three-phase voltage unbalance and distribution transformer overload caused by single-phase access of high permeability distributed photovoltaics in the Greenvale distribution station area in Australia. Through scheme design and control strategy research, a comprehensive management scheme for SVG, EES, PSD and an intelligent terminal controller are proposed, and engineering application is carried out to verify the governance effect.

2 System scheme

The system scheme is divided into three layers, comprising a station control layer (background master station), a central control layer (intelligent terminal controller) and

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a local control layer (SVG, EES, PSD). Figure 1 shows the system architecture. The system uses a LoRa wireless communication network and the intelligent terminal controller to control the SVG, EES, and PSD to solve the problems of distribution transformer overload, voltage over-limit and three-phase unbalance. The intelligent terminal controller has the functions of data processing, logical judgment, and communication with the background master station, while the background master station monitors the operational condition and stores the data of the low-voltage distribution networks.

2.1 Operating principle of PSD

As shown in Fig. 2, a main control switch is installed at the output terminal of the distribution transformer to monitor the three-phase unbalance and issue adjustment commands. The PSDs are installed at the front ends of the users along the branch circuits to monitor the load information and conduct corresponding phase-change operation according to the command.

2.2 Principle of SVG three-phase unbalance compensation

As shown in Fig. 3, the load current is detected in real time by an external current transformer (CT), and is sent to the controller for processing and analysis to determine whether the load is unbalanced, and to calculate the required compensating phase current. The controller then sends signals to SVG power circuits to transfer the unbalanced current from the phase with large current to the phase with small current, to balance the three phases.

2.3 Principle of SVG reactive power compensation

As shown in Fig. 4, the load current is measured and its reactive content is analyzed. To compensate for the load reactive current, the SVG then generates an opposite current to be injected into the grid.

3 Control strategies research

3.1 Transformer overload control strategy

In the case of transformer overload, the reactive power of the SVG and the reactive and active power of the EES converter (PCS) are adjusted to reduce the output power of the distribution transformer. The control flow chart is shown in Fig. 5a. As seen there, the apparent power of the transformer low voltage side S_G is calculated in real time. If $S_G > K S_T$ (K can be set to, e.g. 0.8, and S_T is the rated transformer capacity), the power factor of the transformer low-voltage side is analyzed and compared to the set value. If the power factor is lower than the set value, SVG reactive power compensation is provided to improve the transformer power factor to be higher than the set value. In the event of insufficient SVG reactive power capability, the required reactive power is provided by PCS. According to the difference of S_G and $K S_T$, the active power of PCS is then set accordingly to ensure $S_G < K S_T$.

3.2 Bus overvoltage control strategy

In the case of overvoltage at the transformer low voltage side, PCS active power and SVG reactive power are adjusted so the output power of the distribution transformer is increased (increase power load) and consequently, the bus overvoltage problem is

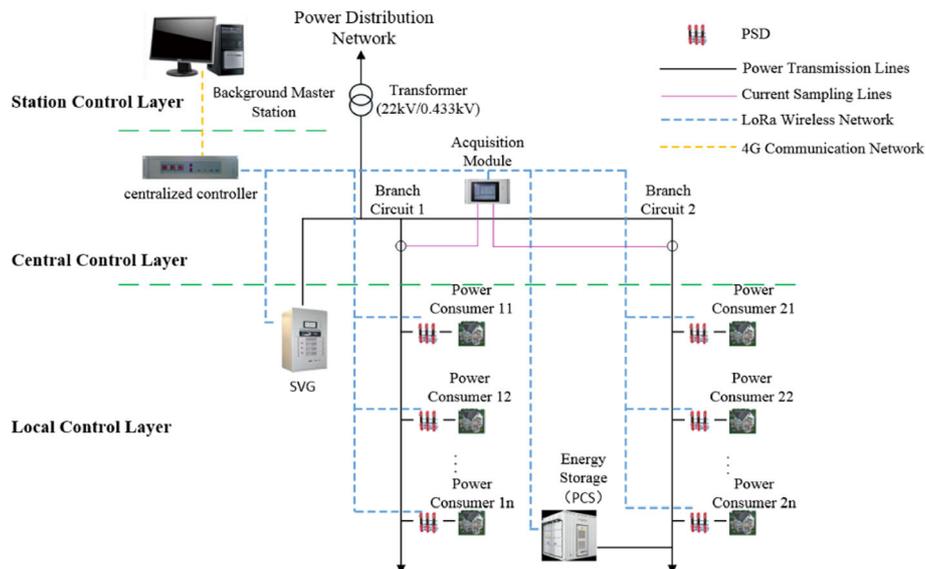


Fig. 1 System architecture

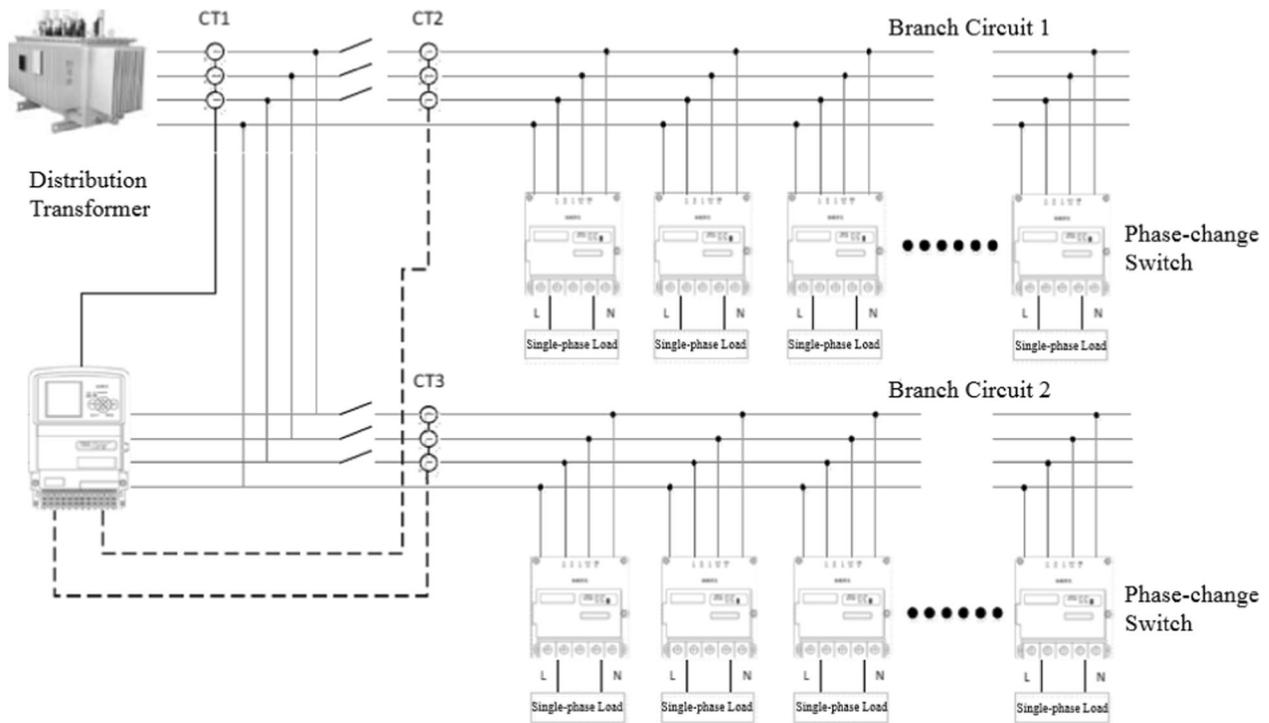


Fig. 2 Operating principle of PSD

solved. The control flow chart is shown in Fig. 5b. As can be seen, when the measured voltage of the transformer low-voltage side is greater than K_1U_N (K_1 generally takes 1.1 and U_N is the nominal voltage), the PCS active power is adjusted gradually according to a fixed step size, and if overvoltage still exists, SVG reactive power is further successively adjusted by a fixed step.

3.3 Bus under-voltage control strategy

In the case of under-voltage, the SVG reactive power and PCS active power are adjusted so the output power of the distribution transformer is reduced (reduced power load) and the bus under-voltage problem is solved. The control flow chart is shown in Fig. 5c. As shown, when voltage of less than K_2U_N (K_2 generally takes 0.9) is detected, the SVG reactive power is

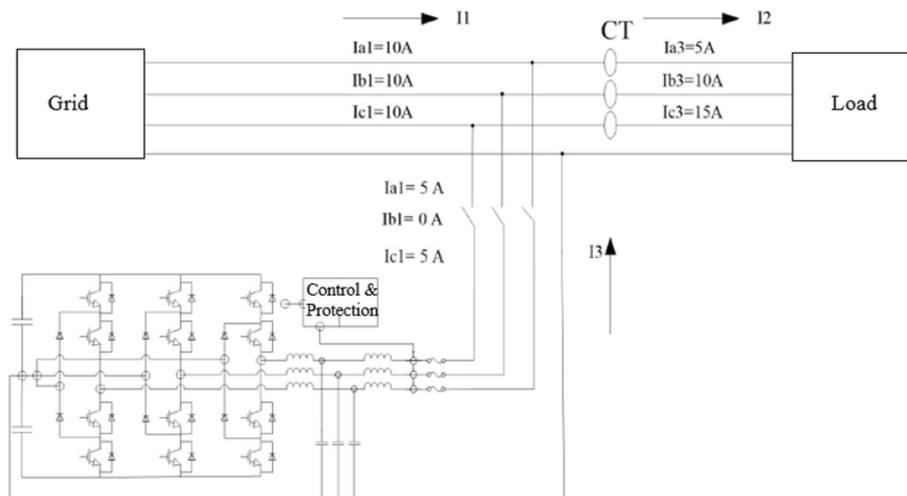
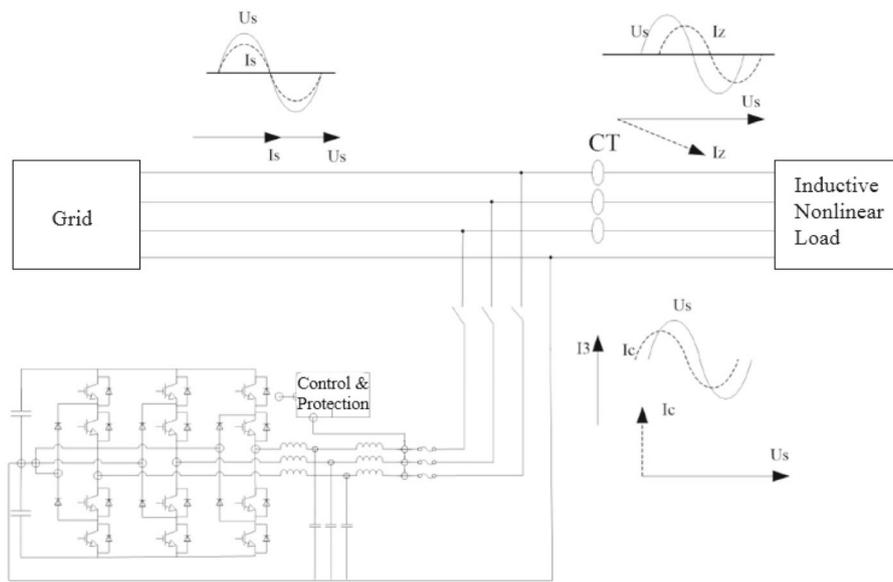
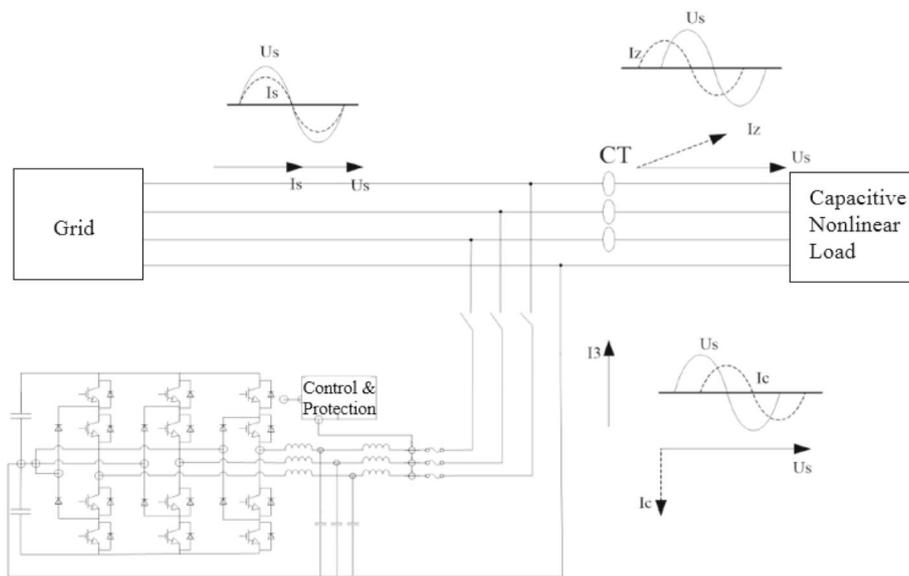


Fig. 3 Principle of SVG three-phase unbalance compensation



a. Inductive reactive power compensation



b. Capacitive reactive power compensation

Fig. 4 Principle of SVG reactive power compensation. **a.** Inductive reactive power compensation. **b.** Capacitive reactive power compensation

adjusted successively according to a fixed step size, and if under-voltage still exists, the PCS active power is further adjusted successively by fixed steps.

3.4 Anti-countercurrent control strategy

By setting an anti-countercurrent threshold value, active power can be prevented from being sent back to the large power grid. The control flow chart is shown in Fig. 5d. As can be seen, when the exchanged power through

the point of common coupling (PCC) exceeds the threshold value, the discharge power of the energy storage device is reduced or the charging power of the energy storage device is increased.

3.5 SOC maintenance control strategy

When the transformer voltage and loading rate are in normal states, the active power of the PCS is controlled to keep the SOC within its normal range (typically, 40%

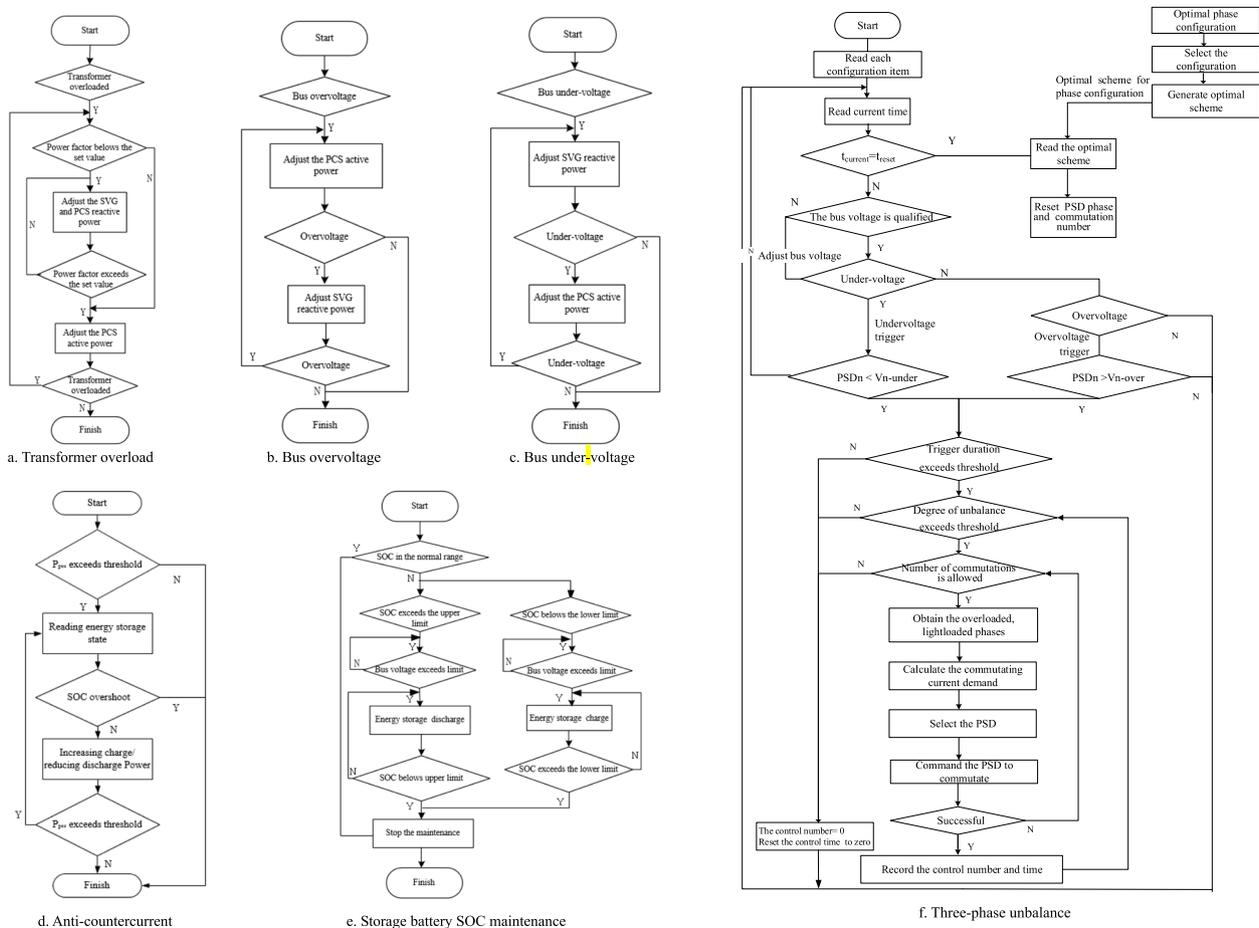


Fig. 5 Control strategy flow charts. **a** Transformer overload. **b** Bus overvoltage. **c** Bus under-voltage. **d** Anti-countercurrent. **e** Storage battery SOC maintenance. **f** Three-phase unbalance

~ 60%). The control flow chart is shown in Fig. 5e. As can be seen, when the SOC is greater than 60% and the bus voltage is less than $1.0U_N$ (adjustable), the PCS discharges at a pre-defined active power value. In contrast, when the SOC is less than 40% while the bus voltage is greater than $1.0U_N$ (adjustable), the PCS charges at a pre-defined active power value.

3.6 Three-phase unbalance control strategy

At a specific time each day, all the phase switching devices are switched to the “best position” according to the analysis of historical data. Reset time and best position are adjustable parameters, and the control strategy flow chart is shown in Fig. 5f. As can be seen, it first determines whether the current time is within the set time period, and whether PSD is over or under-voltage and the duration exceeds the set threshold. No phase change regulation will be carried out unless both current unbalance and duration are

greater than the corresponding thresholds. If current unbalance and duration both exceed their thresholds, the controller calculates the heavy load phase and light load phase, and selects the best commutation switch according to the branch current.

4 Engineering application results and discussion

4.1 Engineering application

An engineering application has been carried out in the Greenvale low-voltage distribution networks in Australia with high permeability distributed photovoltaics. SVG, EES, PSD and an intelligent terminal controller have been installed, and the site configuration is shown in Fig. 6. The distribution transformer capacity is 200kVA, the EES system capacity is 100 kW / 200kWh, and the SVG capacity is 100kVar. Through LoRa wireless communication, the intelligent terminal controller is able to improve the power quality of the low voltage distribution networks through coordination with the PCS, SVG and PSD.

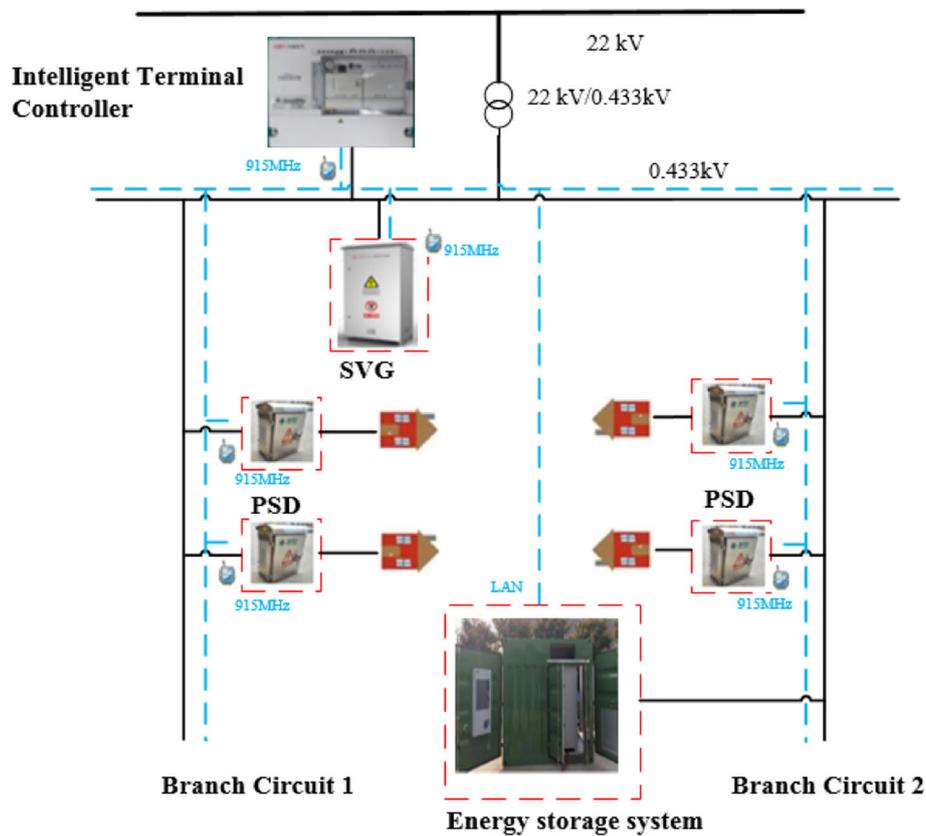


Fig. 6 Schematic diagram of engineering application site configuration

5 Discussion

The intelligent terminal controller monitors the operation data of low-voltage distribution networks in real time, determines the type of power quality problem according to the set thresholds, and controls the PCS, SVG and PSD.

When the transformer low-voltage side apparent power and power factor exceed the set values, the transformer overload control system is initiated. The reactive power from the SVG, and reactive and active power from the PCS are adjusted to reduce the output power of the transformer and solve the transformer overload problem.

When the voltage on the transformer low-voltage side exceeds the set value, the bus over/under voltage control is initiated. PCS active power and SVG reactive power

are adjusted to change the output power of the transformer and restore the bus voltage to its normal range.

When an over/under voltage phenomenon occurs in the PSD and the duration exceeds the threshold, while at the same time, the unbalance value and duration of branch current also exceed the thresholds, the intelligent terminal controller calculates the optimal PSD and issues a command to conduct the commutation operation.

Table 1 compares the experimental data before and after power quality enhancement. It can be seen that power quality has been significantly improved by the enhancement control. The three-phase unbalance degree is now less than 5%, the voltage fluctuation is less than 5%, and the distribution transformer overload phenomenon is also improved.

Table 1 Comparison of experimental data before and after power quality enhancement

Low-voltage Distribution Networks	Three-phase Unbalance Degree %		Bus Voltage V		Power Factor		Transformer Overload kW	
	before	after	before	after	before	after	before	after
Typical day 1	15.6	2.8	258	243	0.69	0.95	180	156
Typical day 2	22.4	3.2	228	242	0.72	0.96	182	159

6 Conclusion

To address the problems of transformer overload, bus over/under voltage, anti-counter-current, SOC maintenance, and three-phase unbalance caused by high permeability distributed photovoltaic access in low-voltage distribution networks, an integrated control scheme using SVG, EES, PSD and intelligent terminal controller has been studied. Analysis of the experimental data and engineering application has validated its good control effects and economic benefit for treating power quality problems. Combined with data analytics and artificial intelligence technologies, intelligent management and analysis of power quality in low-voltage distribution network will be studied in future work.

Abbreviations

SVG: Static var generator; PSD: Phase switching device; EES: Electric energy storage; CT: Current transformer; PCS: Power conditioning system; SOC: State of charge; PCC: Point of common coupling

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Authors' contributions

RL as the first author, provided critical comments and technical guidance of the paper, PW helped to provide engineering application information and improve the paper quality, KW as the corresponding author, contributed significantly to the technical research, writing and submission of the paper. BL helped to improve the paper quality, FY provided control strategy research and also helped to improve the paper quality. The authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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