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Comprehensive benefit optimization method for photovoltaic inverters participating in distribution network loss reduction by reactive compensation

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When a large number of distributed photovoltaic (PV) systems are integrated into the distribution network, power flow becomes bidirectionally fluctuating, resulting in variable line losses. In the scenario of reverse flow, the increase in line loss is particularly significant. The bidirectional reactive power regulation of photovoltaic inverters is an effective approach to reduce losses in the distribution network. However, despite the benefits of reducing losses, reactive power regulation by photovoltaic inverters also incurs additional costs. Therefore, there is a need for research into a comprehensive benefit optimization method for inverters participation in reducing reactive power losses in distribution networks. Firstly, the cost quantification models for the investment, transformation, operation, and lifespan loss of the photovoltaic inverters involved in reactive power loss reduction are established. Secondly, the benefit quantification models for loss reduction and power factor improvement are developed. Thirdly, considering various operational scenarios of both photovoltaic systems and loads, a comprehensive benefit optimization method for photovoltaic inverters participating in reactive power loss reduction in distribution networks is proposed. Finally, through example analysis, the cost and benefit are calculated and fitted in different scenarios, and the optimization calculation is carried out. Compared to the scenario where the photovoltaic inverter operates at the maximum reactive power regulation capacity, the optimized comprehensive benefit is increased by 21.20%. The proposed method is validated to effectively enhance the comprehensive benefits of inverters participation in reactive power loss reduction.

KEYWORDS

benefit optimization, cost and benefit analysis, loss reduction by reactive compensation, multiple operational scenarios, photovoltaic inverters

1 Introduction

With the large-scale integration of distributed photovoltaic (PV) systems, the power flow distribution within the distribution network frequently fluctuates, leading to a significant increase in line losses. When the output of photovoltaics far exceeds the load, power is back-fed from the distribution network to the main grid, causing a

significant increase in line losses. Urgent reactive power adjustment is needed to reduce these losses (Elseify et al., 2023; Kondo and Baba, 2020; Nwaigwe et al., 2019; Sivalingam et al., 2017). Currently, due to the high investment costs associated with dynamic reactive compensation devices, there are relatively few installations of Static Var Compensators (SVC) or Static Synchronous Generators (SVG) within distribution networks (Wang et al., 2021; Wong et al., 2019). The flexibility of adjusting capacitance and reactance is relatively low. Therefore, it is imperative to explore new types of reactive power sources for loss reduction. Photovoltaic inverters, with their technical advantages in bidirectional reactive power regulation, provide an effective means to achieve local reactive power balance and reduce losses in the distribution network (Kumar and Singh, 2021). However, the reactive power regulation of PV inverters will incur adjustment costs. It is urgent to comprehensively consider the loss reduction benefits and costs, and study methods for optimizing comprehensive benefits.

In the context of reactive power control in photovoltaic power plants (Samadi et al., 2012; Li et al., 2024), addresses challenges arising from the growing integration of PV systems into the grid, highlighting that existing PV models often assume these systems operate at a power factor of 1 according to current standards. This paper outlines a non-proprietary process for modeling three-phase single-stage photovoltaic systems, encompassing control scheme design, and evaluates key aspects and impacts of three distinct reactive power regulation strategies. Existing research has demonstrated the capabilities of photovoltaic inverters to control reactive power while producing active power. In terms of reactive power compensation and loss reduction technologies within distribution networks (Ibram and Gueorgiev, 2021), explores how to adjust the operational parameters of STATCOM to achieve reactive power compensation for the photovoltaic system, thereby effectively enhancing the operational stability of the photovoltaic systems and the overall power quality of the grid. Reference (Chen, 2018) focuses on improving power quality and line losses in a 35 kV distribution network using static reactive power generators and capacitors as reactive devices. Reference (Ahsan et al., 2012) discusses the optimization and stabilization of power quality, power factor, and network line losses in wind power systems utilizing SVC/SCG as reactive power sources. Reference (Wang et al., 2023; Pan et al., 2024) addresses reactive power configuration issues in photovoltaic generation systems but does not investigate the inherent reactive regulation capabilities of the PV systems themselves.

In the area of cost quantification and benefit analysis of reactive power compensation in distribution networks Meliopoulos et al. (1999); Dona and Paredes (2001), analyze the reactive support costs incurred by various energy suppliers to improve voltage stability across the network. (Ji et al., 2017; Masikana et al., 2024; Samadi et al., 2014) establish a reactive pricing model for generators based on the P-Q characteristics of doubly-fed wind turbines and synchronous motors, proposing a segmented pricing strategy for reactive power in doubly-fed turbines under fluctuating wind speeds. In summary, there is relatively little research on the cost and benefit analysis of photovoltaic inverters participating in reactive power regulation.

The main contributions and innovative points of this paper are as follows:

1. The constant and variable costs of reactive power regulation in photovoltaic inverters are quantified.
2. The economic benefits of photovoltaic inverters participating in loss reduction by Reactive Compensation are quantified in different operating scenarios, including direct and indirect benefits.
3. By considering both the adjustment costs and the benefits of loss reduction, comprehensive benefit optimization method for photovoltaic inverters participating in distribution network loss reduction by reactive compensation is proposed.

2 Economic and technical feasibility analysis of photovoltaic inverters participating in reactive power loss reduction in distribution networks

2.1 Technical feasibility

- (1) Bidirectional Reactive Power Regulation Capabilities of Photovoltaic Inverters

Currently, many inverters operate under a constant power factor (CPF) mode. Taking a power factor of 0.95 as an example, the output reactive power varies between $\pm 31.33\%$. When using a variable power factor control mode, during nighttime when the photovoltaic output is zero, the theoretical value of reactive power output can reach $\pm 100\%$. At other times, the reactive power output of the inverter is influenced by the active power output [Samadi et al. (2012)].

- (2) The technical feasibility of reactive power loss reduction by photovoltaic inverters.

The losses in distribution lines are shown in Formula 1:

$$\Delta P = \left(\frac{P^2 + Q_T^2}{U^2} \right) R = \left(\frac{P^2 + (Q_L - Q_S)^2}{U^2} \right) R \quad (1)$$

Where Q_T , Q_L , Q_S are the variables represent the reactive power transmitted through the line, the reactive power of the load, and the reactive power local compensated by the inverter. By balancing the reactive power demand of the load on-site, the inverter can reduce the active power losses caused by reactive power transmission along the line. Additionally, reactive power compensation can also increase the voltage of each node, thereby further reducing losses.

2.2 Economic feasibility

When photovoltaic inverters participate in reactive power loss reduction, both the benefits and costs increase, as shown in Table 1. The benefits of distributed photovoltaics participating in reactive power loss reduction are divided into two parts, namely, direct benefits and indirect benefits. Direct benefits refer to the energy-saving benefits brought by the loss reduction during the statistical period. Indirect benefits refer to the electricity price discounts obtained by the users when the power factor is improved.

TABLE 1 Economic analysis of inverter participation in reactive power loss reduction.

Type	Content
Direct Benefits	Equivalent economic benefits of reducing losses
Indirect Benefits	Discounts on electricity bills resulting from improved power factor
Costs	Various costs increment
Comprehensive Benefits	Direct benefits + Indirect benefits - Costs

When photovoltaic inverters participate in reactive power loss reduction, it will lead to an increase in their operating costs, including: the capital investment costs of equipment that should be allocated to the use of reactive power regulation functions, the renovation costs incurred from developing regulation functions; the loss costs associated with the use of reactive power regulation functions; and the lifespan deterioration costs caused by utilizing reactive power regulation functions.

When the comprehensive benefits are positive, it is economically feasible for photovoltaic inverters to participate in reactive power loss reduction, and the maximization of comprehensive benefits should be pursued.

3 Comprehensive benefit optimization model

3.1 Cost model

(1) Investment Costs

When the reactive power output function is enabled, it occupies the active output capacity of the photovoltaic equipment. The capital investment cost of distributed photovoltaic equipment should be allocated between active and reactive power transmission functions.

First, the capital investment cost of the inverter is allocated to the investment cost for each period according to its designed service life, as shown in Formula 2:

$$R = \lambda^*(D - M - v) \tag{2}$$

Where D represents the capital investment cost of the inverter; R is the investment cost allocated for each period; M is the cumulative allocated cost for the current period; v is the estimated residual value; and λ is the depreciation rate.

Next, the opportunity cost for each period is calculated as shown in Formula 3:

$$F = D^*(1 + C_{av})^m - D \tag{3}$$

Where F represents the opportunity cost for each period; C_{av} is the average investment return in society; and m is the current interest period.

Finally, the investment cost allocated for the reactive power loss reduction function for each period is calculated as Formula 4 and recorded as C_1 .

$$C_1 = \beta(F + R) \tag{4}$$

Where β is the allocation coefficient.

(2) Transformation Costs

The existing distributed photovoltaic equipment only needs to upgrade the inverter control software without replacing hardware, and can have bidirectional reactive power output function.

First, the total transformation cost is calculated as shown in Formula 5:

$$C_2\Sigma = \frac{o^*d^*b}{T} + E \tag{5}$$

Where T represents the number of distributed photovoltaics in a certain distribution network; o is the number of personnel involved in the upgrade; d is the number of working days; b is the labor cost per person per day; and E is the software upgrade fee for a single distributed photovoltaic.

Next, the transformation cost for each period is calculated as shown in Formula 6:

$$C_2 = \frac{2}{N} * (C_2\Sigma - M_2\Sigma - v_2\Sigma) \tag{6}$$

Where N represents the total number of allocation periods; $M_2\Sigma$ and $v_2\Sigma$ represent the cumulative allocated cost and the cumulative residual value, respectively. Using the accelerated depreciation principle and considering the decline in equipment value or production efficiency due to technological and market factors, it is necessary to allocate more costs in the earlier periods. Therefore, the depreciation rate is taken as $2/N$.

(3) Operating Loss Costs

When participating in reactive power regulation, a larger ripple current increment is generated on the DC side, leading to an increase in the heating losses of electrolytic capacitors and equipment.

The power loss caused by reactive power transmission is calculated as Formula 7:

$$\Delta P_Q = \left(\frac{\sqrt{P^2 + Q^2}}{U_N} - \frac{P}{U_N} \right)^2 \times R_C \tag{7}$$

Where P and Q represent the active operating value and the reactive operating value of the inverter, respectively. U_N is the rated voltage of the grid, and R_C represents the equivalent resistance.

The reactive power operating loss costs for each period is calculated as Formula 8:

$$C_3 = \Delta P_Q * T * X_P \tag{8}$$

Where T represents the statistical cycle, and X_P is the feed-in tariff for photovoltaic.

(4) Lifespan Loss Costs

The limiting factor affecting the lifespan of distributed photovoltaics is the lifespan of the DC-side capacitors, which is significantly influenced by temperature.

The lifespan of the electrolytic capacitors before participating in reactive power loss reduction is calculated as shown in [Formula 9](#):

$$K = K_0 * 2^{\frac{T_{max} - T_a}{10}} \quad (9)$$

Where T_{max} and K_0 represent the maximum rated temperature and the corresponding estimated lifespan, respectively. T_a is the actual operating temperature of the capacitor.

The temperature of the inverter is calculated as shown in [Formula 10](#):

$$T_a = T_s + R * P_s \quad (10)$$

Where T_s is the room temperature, R is the thermal resistance between the inverter and the atmosphere, and P_s is the loss power.

The temperature increment of the inverter caused by reactive power output is calculated as shown in [Formula 11](#):

$$\Delta T_a = T_s + R * \Delta P_Q \quad (11)$$

The useable lifespan after participating in reactive power loss reduction is calculated as shown in [Formula 12](#):

$$K' = K_0 * 2^{\frac{T_{max} - T_a - \Delta T_a}{10}} \quad (12)$$

The lifespan loss cost per period is calculated as shown in [Formula 13](#):

$$C_4 = \left[\frac{2 \times t}{K'} (D_C - M_C - v_c) - \frac{2 \times t}{K} (D_C - M_C - v_c) \right] \quad (13)$$

Where D_C is the purchase price of the electrolytic capacitors, M_C is the already allocated cost, and v_c is the residual value, t is selected as the statistical interval.

In summary, the cost function for the distributed photovoltaic participating in reactive power loss reduction is established as [Formula 14](#) and denoted as C :

$$C = C_1 + C_2 + C_3 + C_4 \quad (14)$$

3.2 Benefit model

(1) Benefit of loss reduction

First, the source-load operating scenarios are defined, and the loss reduction effect of inverter reactive power compensation is modeled under each scenario. The active power of distributed photovoltaics are categorized into large-scale, medium-scale, and small-scale scenarios. The loads are divided into large-scale and small-scale scenarios, leading to a total of six combined operating scenarios.

In these six scenarios, the line loss rate of the distribution network before the inverter participates in the regulation is calculated as σ_{n0} (where n represents different scenario numbers). Then, the line loss rate of the distribution network after the inverter participates without compensation is calculated as σ_n .

The line loss rate of the distribution network varies depending on the reactive power compensation capacity. The function

mapping relationship between reactive power of photovoltaic inverters and line loss rate is established using polynomial fitting, as shown in [Formula 15](#). The goodness-of-fit is defined as the ratio of the regression sum of squares to the total sum of squares. When the goodness-of-fit is greater than or equal to 0.99, the fitting is complete.

$$\sigma_n = f_n(Q) \quad (15)$$

Next, the loss reduction quantity in the n -th scenario is calculated as [Formula 16](#):

$$\Delta L_n = T_L \left(\frac{P_n}{1 - \sigma_{n0}} * \sigma_{n0} - \frac{P_n}{1 - \sigma_n} * \sigma_n \right) \quad (16)$$

Where P_n is the grid-connected power in the n -th scenario, T_L is the duration of the n -th scenario.

Finally, the total loss reduction benefit during the statistical period is calculated as [Formula 17](#):

$$B_1 = \sum_{n=1}^6 \Delta L_n * X_{SALE} \quad (17)$$

Where X_{SALE} represents the electricity price during the statistical period.

(2) Benefit of power factor improvement

Based on the principle of electricity price adjustment according to the power factor, the formula for calculating the electricity price adjustment coefficient is as [Formula 18](#):

$$\alpha = \begin{cases} -0.0075 + [96 - 100 \cos \theta] \times 0.0015 & \cos \theta \in (0.9, 1] \\ [91 - 100 \cos \theta] \times 0.005 & \cos \theta \in (0.8, 0.9] \end{cases} \quad (18)$$

In the n -th scenario, the functional relationship between the reactive power capacity and the power factor is established as shown in [Formula 19](#):

$$\cos \theta_n = g_n(Q) \quad (19)$$

According to [Formula 19](#), the power factors before and after the reactive power regulation of the photovoltaic inverter for the n -th scenario are calculated and denoted as $\cos \theta_{n0}$ and $\cos \theta_n$, respectively. Then, using [Formula 18](#), the electricity price adjustment coefficients before and after the reactive power regulation are calculated and denoted as α_{n0} and α_n .

The benefit of power factor improvement allocated to distributed photovoltaic enterprises for each period is calculated as [Formula 20](#):

$$B_2 = \varepsilon * L_n * X * (\alpha_{n0} - \alpha_n) \quad (20)$$

Where L_n represents the total electricity consumption of industrial users during the statistical period, X is the benchmark electricity price for industrial users, and ε is the allocation coefficient.

In summary, the benefit function for distributed photovoltaics participating in reactive power regulation is established as [Formula 21](#):

$$B = B_1 + B_2 \quad (21)$$

3.3 Comprehensive benefit optimization

Based on the cost model and the benefit model, the comprehensive benefit of distributed photovoltaics participating in reactive power loss reduction is calculated and denoted as [Formula 22](#):

$$H = B - C \tag{22}$$

Where H , B , and C are all functions of Q . The optimization objective of this paper is to maximize the benefit. The value of Q is constrained by its maximum reactive power capacity and the inverter capacity, as shown in [Formula 23](#):

$$\begin{cases} |Q| \leq Q_{\max} \\ |Q| \leq \sqrt{S^2 - P^2} \end{cases} \tag{23}$$

3.4 Model solution

The genetic algorithm (Ji et al., 2022) is adopted to solve this model, and the flowchart is shown in [Supplementary Figure S1](#).

4 Example analysis

A distribution network containing distributed photovoltaic systems is built, taking the 33-node system as an example, where the distributed photovoltaics are connected to nodes 4, 5, 8, 9, 10, 12, 20, 21, 22, 24, 25, 26, 28, 30, 32, and 33. A 24-h period is selected as the statistical interval. The operating scenarios for distributed photovoltaics and loads are set as shown in [Supplementary Tables S1–S5](#). The results of dividing source-load operating scenarios are as follows:

- Scenario 1: Distributed photovoltaic 5,355 kW, load 1,030 kW;
- Scenario 2: Distributed photovoltaic 5,355 kW, load 5,800 kW;
- Scenario 3: Distributed photovoltaic 2,520 kW, load 5,800 kW;
- Scenario 4: Distributed photovoltaic 2,520 kW, load 1,030 kW;
- Scenario 5: Distributed photovoltaic 315 kW, load 5,800 kW;
- Scenario 6: Distributed photovoltaic 315 kW, load 1,030 kW.

4.1 Cost calculation

In the simulation case, the specific parameters are shown in [Table 2](#). According to [Formulas 2–13](#), various costs are calculated.

$$\begin{aligned} C_1 &= \beta(F + B) = 395.9792\text{¥} \\ C_2 &= \frac{2}{N} * (C_2 \Sigma - M_2 \Sigma - v_2 \Sigma) = 92.8889\text{¥} \\ C_3 &= 0.2028 \times \left[\left(\frac{\sqrt{P^2 + Q^2}}{220} \right)^2 - \frac{P}{220} \right]^2 \\ C_4 &= 24 \times \left(2^{\frac{Q}{15000}} - 1 \right) \end{aligned}$$

4.2 Revenue calculation

The reactive power output of the converters is adjusted in the different scenarios, and the corresponding line loss rates and power factors are obtained through simulation.

TABLE 2 Inverter parameters.

Inverter parameters	Value
Total Capacity of Distributed PV Station (S)	6 MW
Initial Investment for PV Inverter (D)	120,000 ¥
Bidirectional Reactive Power Capacity (Q)	50% of S
Lifespan of Electrolytic Capacitor (U)	10,000 h at 60°C
Price of Electrolytic Capacitor (D_c)	1,250 ¥ per unit
Lifespan of Inverter/Converter	20 years
Estimated Residual Value of C_1	5%
Daily Cost of Renovation Workers (b)	900 ¥
Number of Workers for Upgrade (o)	4
Working Days per Worker (d)	4
Software Upgrade Cost per Device (E)	1,250 ¥
Grid-connected Electricity Price for PV (X_p)	0.3 ¥/kWh
Social Average Investment Return Rate (C_{AV})	0.35%
Residual Value of C_4	0%
Residual Value of C_2	0%
Resistance of capacitance of the inverter (R_c)	0.1 Ω
Normal Operating Temperature of Inverter (T_n)	40°C
Temperature Variation of Inverter	1,500 var/degree

Based on [Table 3](#), the function of the line loss rate with respect to the reactive power output in Scenario 1 is fitted as follow:

$$\sigma_1 = f_1(Q) = 4 \times 10^{-13}Q^3 + 6 \times 10^{-9}Q^2 - 3 \times 10^{-5}Q + 0.2502$$

Based on [Table 3](#), the function of the power factor with respect to the reactive power output in Scenario 1 is fitted as follow:

$$\begin{aligned} \cos \theta_1 &= g_1(Q) \\ &= 3.3534 \times 10^{-12}Q^3 - 1.1353 \times 10^{-8}Q^2 - 9.1088 \times 10^{-5}Q \\ &\quad + 0.89028 \end{aligned}$$

Based on [Table 4](#), the function of the line loss rate with respect to the reactive power output in Scenario 2 is fitted as follow:

$$\begin{aligned} \sigma_2 &= f_2(Q) \\ &= -2.123 \times 10^{-10} \times Q^3 + 2.07 \times 10^{-7} \times Q^2 - 0.0000526 \times Q \\ &\quad + 0.01371 \end{aligned}$$

Based on [Table 4](#), the function of the power factor with respect to the reactive power output in Scenario 2 is fitted as follow:

$$\cos \theta_2 = g_2(Q) = -1.02795 \times 10^{-6} \times Q^2 + 0.001028 \times Q + 0.7334$$

Based on [Table 5](#), the function of the line loss rate with respect to the reactive power output in Scenario 3 is fitted as follow:

$$\sigma_3 = f_3(Q) = 10^{-13}Q^3 + 4 \times 10^{-9}Q^2 - 2 \times 10^{-5}Q + 0.0424$$

TABLE 3 Reactive power, line loss rate, and power factor in scenario 1.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	25.02%	0.8904
-153.73	24.58%	0.9040
-312.32	24.14%	0.9174
-477.11	23.73%	0.9307
-649.94	23.33%	0.9437
-833.44	22.96%	0.9564
-1,031.66	22.6%	0.9686
-1,251.45	22.28%	0.9801
-1,506.16	22.00%	0.9903
-1830.49	21.79%	0.9982
-2,593.54	21.99%	0.9917

TABLE 4 Reactive power, line loss rate, and power factor in scenario 2.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	1.37%	0.7435
100.00	1.35%	0.8156
200.00	1.34%	0.8878
300.00	1.33%	0.9504
400.00	1.33%	0.9909
500.00	1.33%	0.9985
600.00	1.35%	0.9714
900.00	1.42%	0.7789

TABLE 5 Reactive power, line loss rate, and power factor in scenario 3.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	4.24%	0.7437
600.00	3.28%	0.8075
900.00	2.91%	0.8407
1,200.00	2.62%	0.8737
1,500.00	2.40%	0.9055
1800.00	2.24%	0.9347
2,100.00	2.16%	0.9600
2,400.00	2.13%	0.9800
2,700.00	2.18%	0.9933

TABLE 6 Reactive power, line loss rate, and power factor in scenario 4.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	4.24%	0.9708
100.00	4.16%	0.9822
200.00	4.11%	0.9899
300.00	4.10%	0.9997
320.00	4.09%	0.9999
600.00	4.16%	0.9999
900.00	4.46%	0.9999

TABLE 7 Reactive power, line loss rate, and power factor in scenario 5.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	4.24%	0.7437
600.00	3.28%	0.8075
900.00	2.91%	0.8407
1,200.00	2.62%	0.8737
1,500.00	2.40%	0.9055
1800.00	2.24%	0.9347
2,100.00	2.16%	0.9600
2,400.00	2.13%	0.9800
2,700.00	2.18%	0.9933

Based on Table 5, the function of the power factor with respect to the reactive power output in Scenario 3 is fitted as follow:

$$\begin{aligned} \cos \theta_3 &= g_3(Q) \\ &= -1.15732 \times 10^{-8} \times Q^2 + 0.000127 \times Q + 0.739667 \end{aligned}$$

Based on Table 6, the function of the line loss rate with respect to the reactive power output in Scenario 4 is fitted as follow:

$$\sigma_4 = f_4(Q) = 0.042367 + 5 \times 10^{-13}Q^3 + 10^{-8}Q^2 - 8 \times 10^{-6}Q$$

Based on Table 6, the function of the power factor with respect to the reactive power output in Scenario 4 is fitted as follow:

$$\begin{aligned} \cos \theta_4 &= g_4(Q) \\ &= -8.65055 \times 10^{-8} \times Q^2 + 0.0001065 \times Q + 0.972385 \end{aligned}$$

Based on Table 7, the function of the line loss rate with respect to the reactive power output in Scenario 5 is fitted as follow:

$$\sigma_5 = f_5(Q) = 0.1006 + 1 \times 10^{-12}Q^3 - 1 \times 10^{-9}Q^2 - 1 \times 10^{-5}Q$$

Based on Table 7, the function of the power factor with respect to the reactive power output in Scenario 5 is fitted as follow:

$$\begin{aligned} \cos \theta_5 &= g_5(Q) \\ &= -8.293368 \times 10^{-9} \times Q^2 + 6.83512 \times 10^{-5} \times Q + 0.871616 \end{aligned}$$

TABLE 8 Reactive power, line loss rate, and power factor in scenario 6.

Reactive power of photovoltaic (kvar)	Line loss rate	Power factor
0.00	0.67%	0.9096
100.00	0.60%	0.9451
200.00	0.56%	0.9782
320.00	0.53%	0.9999
600.00	0.64%	0.9999
900.00	1.03%	0.9999

Based on Table 8, the function of the line loss rate with respect to the reactive power output in Scenario 6 is fitted as follow:

$$\sigma_6 = f_6(Q) = 0.0067 + 10^{-8} \times Q^2 - 8 \times 10^{-6}Q + 3 \times 10^{-12}Q^3$$

Based on Table 8, the function of the power factor with respect to the reactive power output in Scenario 6 is fitted as follow:

$$\begin{aligned} \cos \theta_6 &= g_6(Q) \\ &= -2.56766 \times 10^{-7} \times Q^2 + 0.000318 \times Q + 0.916213 \end{aligned}$$

The functions $f_1(Q) \sim f_6(Q)$ are substitute into Formulas 15–17 to calculate the loss reduction benefit B_1 for the statistical period.

The functions $g_1(Q) \sim g_6(Q)$ are substitute into Formulas 18–20 to calculate the power factor improvement benefit B_2 .

4.3 Comprehensive benefit optimization and result analysis

With the goal of maximizing comprehensive benefits, global optimization is performed through the rotation of six scenarios over a 24-h period. The step size is set to 2 h. The optimization results are shown in Supplementary Figure S2.

An average reactive power adjustment in Scenario 6 is 290.67 kvar, which is from 0:00 to 6:00. From 6:00 to 10:00 is Scenario 4, with a reactive power adjustment of 2,332 kvar; from 10:00 to 12:00 is Scenario 2, with a reactive power adjustment of 3,000 kvar; from 12:00 to 14:00 is Scenario 1, with a reactive power adjustment of 2022 kvar; from 14:00 to 20:00 is Scenario 3, with a reactive power adjustment of 1769.67 kvar; from 20:00 to 24:00 is Scenario 6, with a reactive power adjustment of 557 kvar.

Before the participation of photovoltaic inverters in reactive power loss reduction, the line loss rates for the six periods were 25.02%, 1.37%, 4.24%, 4.24%, 10.05% and 0.67%, respectively. The power factors were 0.8904, 0.7434, 0.7437, 0.9708, 0.8726 and 0.9096, respectively. After the participation of photovoltaic inverters in reactive power loss reduction, the line loss rates for the six periods were 21.79%, 1.37%, 2.13%, 4.09%, 7.09% and 0.53%, respectively. The power factors were 0.9982, 0.9985, 0.9800, 0.9990, 0.9882 and 0.9990.

Compared with not participating in reactive power loss reduction, the cost of the inverter increased by 536.8681¥, while

the line losses decreased in all six periods and the power factors improved. The comprehensive benefit amounted to 3,370.3577 ¥. When the photovoltaic inverter participates in loss reduction at the maximum reactive power value of 3,000 kvar throughout the day, its comprehensive benefit is calculated to be 2,655.8340¥, which is less than the optimized result described in this paper.

As shown in Table 3: The line loss rate in Scenario 1 before reactive power regulation reaches as high as 25.02%, and the reduction in losses after reactive power regulation is the most significant. Therefore, it is recommended to focus on reactive power loss reduction control for this scenario during dispatch operations.

5 Conclusion

In response to the problem of increased line loss after distributed photovoltaic integration into the distribution network, photovoltaic inverters are used as reactive power sources to achieve reactive power loss reduction. Taking the improved 33 node distribution network as an example, the comprehensive benefit optimization of reactive power loss reduction was carried out.

Firstly, cost models for investment, renovation, operation and lifespan losses are established. In this example, the total cost of photovoltaic inverters participating in reactive power loss reduction within 1 day is calculated to be 536.8681 ¥.

Secondly, six combined operation scenarios of photovoltaic systems and loads are defined, and the relationship between the reactive power regulation capacity, loss reduction benefits, and power factor improvement benefits is fitted for each operating scenario.

Finally, a comprehensive optimization of revenue and costs is conducted. Compared to the scenario where the photovoltaic inverter operates at the maximum reactive power regulation capacity, the optimized comprehensive benefit is increased by 21.20%. The feasibility of the benefit optimization method proposed in this article has been verified. In the follow-up research, the different benefits brought by different loss reduction effects due to the geographical location of the PV inverter can be further considered, and the revenue distribution within the PV inverter can also be considered.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YL: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. RL: Formal Analysis, Methodology, Validation, Writing–original draft, Writing–review and editing. CL: Data curation, Formal Analysis, Writing–review and editing.

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Conflict of interest

Author CL was employed by State Grid Gansu Electric Power Co.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2024.1502053/full#supplementary-material>

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