A Consideration of the Single-Phase Photovoltaic and Energy Storage Joint Regulation of a Three-Phase Unbalanced Control Strategy in a Power Distribution System

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Abstract: With a large amount of distributed power and energy storage access, the traditional three-phase unbalanced treatment of a power distribution system is mainly aimed at the three-phase unbalance of a load, which cannot effectively address the three-phase unbalance problem of a power distribution network after a large number of single-phase photovoltaic access. Therefore, this paper proposes a three-phase unbalanced treatment strategy for the distribution network, which considers the joint regulation ability of single-phase photovoltaic and energy storage and the regulation ability of a reactive power compensation device. Firstly, the joint regulation ability of single-phase photovoltaic and energy storage under different photovoltaic permeability is analyzed. Secondly, according to the joint regulation ability of single-phase photovoltaic and energy storage and the regulation ability of reactive power compensation device, the three-phase power optimization model is constructed to minimize the three-phase unbalance degree and regulation cost, and the JAYA optimization algorithm is used to solve the model. Finally, the 33-node distribution system is used to verify the effectiveness of the proposed strategy.

Keywords: single-phase photovoltaic and energy storage; power distribution system; three-phase unbalance; JAYA optimization algorithm

1. Introduction

In 2023, the China Electricity Council held the founding meeting of the Power Quality Professional Committee, wherein it was suggested that China’s large-scale access to new energy and the “decentralization” of the power system required the local consumption of energy and power. The new power system is faced with many problems, such as weak voltage and frequency regulation supportability, large fluctuations of source load power, and an off-line power quality index of the distribution network [1]. Power quality measurement indicators mainly include harmonics, voltage deviation, three-phase unbalance, and so on. Three-phase unbalance means that three-phase voltage or current is different in amplitude or the phase angle is not 120°, or both [2].

The harm of a three-phase unbalance to the distribution system is mainly reflected in the following six aspects [3–7]: (1) Increases in the power loss of the distribution transformer, resulting in overheating or burning down of the transformer; (2) Increased line loss, affecting the safe and economic operation of the distribution network; (3) Service life of household appliances affected, leading to electrical failure; (4) Increase in loads of heavy-duty lines and expanded security risks; (5) Negative affect on the stability of communication equipment; and (6) Possible misoperation of relay protection or automatic protection devices. Therefore, it is urgent to effectively address the three-phase unbalance...
problem of the distribution system to ensure the economic operation and high-quality power supply level of the distribution system.

For the three-phase unbalance problem of the power distribution system, some scholars have provided different treatment methods, which can be divided into “source”, “load”, and “network” in three ways. In terms of the “source”, it can alleviate the three-phase unbalance problem by optimizing the allocation of distributed generation, adjusting the reactive power of photovoltaic inverter, combining the active power regulation of energy storage, and so on. Wu et al. [8] established a distributed photovoltaic optimal allocation model that considers the three-phase unbalance and takes photovoltaic capacity ratio, network loss, and voltage stability margin as the objective function. Chen et al. [9] established a three-phase balanced and coordinated optimization control model considering photovoltaic phase-switching, photovoltaic inverter reactive power regulation, and energy storage active power regulation to reduce the three-phase unbalance degree of the distribution network. Gerdroodbari et al. [10] proposed a novel reactive power-based control strategy for single-phase PV inverters to improve voltage unbalance and voltage regulation in low-voltage distribution networks. Li et al. [11] proposed a novel coordinated current and voltage unbalance mitigation approach for networked microgrids that include aggregated PV Systems. Gao et al. [12] proposed a new control topology to maintain the unbalance of the network’s three-phase currents within the distribution codes’ limits by switching the single-phase inverter output between the three phases according to the level of current flows in each network’s phases.

From the point of view of the “load”, which is mainly through the adjustment of load time, switching load access is an effective way to address the three-phase unbalance problem. Kandpal and Boonseng [13,14] proposed a day-ahead EV scheduling strategy that considers EV charging and discharging to alleviate unbalance. Liu et al. [15] established an EV orderly charging model that considers EV travel characteristics; this model can optimize the load profile and reduce three-phase unbalance by controlling the EV access phase and charging power. Antić and Islam [16,17] proposed a strategy to alleviate the three-phase unbalance problem by considering the harmonizing characteristics of PV and EV. A few studies focused on electric heaters as research objects in view of the three-phase balance problem of the electric heater in the room. Li et al. [18] proposed the use of expert control to determine the amount of load switching and switching rules to realize the three-phase balance.

From the point of “network”, on the one hand, the three-phase unbalance problem can be solved by adjusting the output of reactive power compensation equipment on the distribution network side, Zhao et al. [19] proposed a strategy of reactive power optimization of a three-phase unbalanced distribution network with single-phase photovoltaic. Nie et al. [20] proposed a real-time load three-phase unbalanced treatment under high photovoltaic permeability. On the other hand, the three-phase unbalance problem can be solved by intelligent commutation and reconstruction of the distribution network. Fang and Tang [21,22] proposed an intelligent commutation optimization strategy reduce the three-phase unbalanced account for the commutation switch lifetime. Gao, Tong and Yang [23–25] proposed some strategies regarding the three-phase dynamic reconstruction of distribution networks to solve a three-phase unbalance problem.

The research on the three-phase unbalanced governance strategy from the point of the “source” focuses on optimizing the allocation of distributed generation, adjusting the reactive power of the photovoltaic inverter and the active power of energy storage. However, this research rarely considers the active and reactive power regulation capacity of photovoltaic and energy storage under different permeability photovoltaic systems, which rarely combine with reactive power compensation devices to realize common governance, and uses a JAYA optimization algorithm to address the three-phase unbalance problems in related fields. Since the energy storage system can realize the short-term charge and discharge of active power, the combined power generation system formed by the combination of photovoltaic and energy storage can be used as an important resource for active
power and reactive power flow regulation in the active distribution network [26], as more and more single-phase photovoltaic and energy storage are connected to the distribution network, it can be seen that single-phase photovoltaic and energy storage have significant potential for regulation.

Therefore, this paper proposes a three-phase unbalanced treatment strategy for the distribution network, which considers the joint regulation ability of single-phase photovoltaic and energy storage and the regulation ability of reactive power compensation devices. Firstly, the joint regulation ability of single-phase photovoltaic and energy storage under different photovoltaic permeability is analyzed. Secondly, according to the joint regulation ability of single-phase photovoltaic and energy storage and the regulation ability of reactive power compensation device, the three-phase power optimization model is constructed to minimize the three-phase unbalance degree and regulation cost, and the JAYA optimization algorithm is used to solve the model. Finally, the 33-node distribution system is used to verify the effectiveness of the proposed strategy.


2.1. Typical Single-Phase Photovoltaic and Energy Storage Grid-Connected Structure

Common single-phase photovoltaic and energy storage grid-connected structures have two types, one type is the grid-connected photovoltaic and energy storage structure based on DC bus, and the other type is the grid-connected photovoltaic and energy storage structure based on AC bus [27]. Among them, because the grid-connected photovoltaic and energy storage structure based on AC bus is easy to install and expand, is more compatible with the power grid, and is widely used. Therefore, this paper chooses the research object of the single-phase photovoltaic and energy storage grid-connected structure based on an AC bus. The regulation ability of active power and reactive power is analyzed. The schematic diagram of the photovoltaic and energy storage system based on an AC bus is shown in Figure 1.

![Figure 1. Schematic diagram of single-phase photovoltaic and energy storage combined with grid connection.](image)

The photovoltaic system in Figure 1 is composed of a photovoltaic array and a bidirectional inverter, and the energy storage system is composed of the battery bank and bidirectional inverter. The DC electricity emitted by the photovoltaic module is converted into AC electricity through the bidirectional inverter, and the remaining electric energy is converted into DC electricity through the bidirectional inverter of energy storage and stored in the battery bank. The battery bank can also charge and discharge to the power grid through the bidirectional inverter.

2.2. Modeling of Single-Phase Photovoltaic Regulatory Capacity

Single-phase photovoltaic is a distributed photovoltaic with random access to any phase and a capacity of no more than 8 kW [28]. Its maximum active power is affected by
environmental factors such as solar illumination intensity and temperature, so its adjustable range is shown as follows:

\[ 0 \leq P_{PV,l,t} \leq P_{PV,l,t,max} \]  \hspace{1cm} (1)

where \( P_{PV,l,t} \) is the active power of single-phase photovoltaic \( l \) at \( t \) the time, \( P_{PV,l,t,max} \) is the maximum active power of single-phase photovoltaic \( l \) at \( t \) time.

The adjustable reactive power range of a single-phase photovoltaic inverter is limited by the capacity and photovoltaic output of a single-phase photovoltaic inverter [9], as shown in the following formula:

\[
\begin{cases}
Q_{PV,l,t,max} = \sqrt{(S_{PV,l})^2 - (P_{PV,l,t})^2} \\
Q_{PV,l,t,min} = -Q_{PV,l,t,max}
\end{cases}
\]  \hspace{1cm} (2)

where \( Q_{PV,l,t,max} \) is the maximum reactive power of a single-phase photovoltaic inverter \( l \) at \( t \) the time, \( Q_{PV,l,t,min} \) is the minimum reactive power of a single-phase photovoltaic inverter \( l \) at \( t \) the time, and \( S_{PV,l} \) is the rated capacity of a single-phase photovoltaic inverter \( l \).

2.3. Modeling of Energy Storage Control Capacity

Energy storage is an indispensable resource for the flexible regulation of power systems and an indispensable part of new power system planning [29,30].

\[
SOC_{l,t+1} = SOC_{l,t} + \left( \frac{P_{ch,l,t} \eta_{ch}}{G_{l,ESS}} - \frac{P_{dis,l,t}}{\eta_{dis} G_{l,ESS}} \right) \Delta t
\]  \hspace{1cm} (4)

where \( SOC_{l,t+1} \) is the state of charge of energy storage \( l \) at \( t + 1 \) the time, \( SOC_{l,t} \) is the state of charge of energy storage \( l \) at \( t \) the time, \( P_{ch,l,t} \) is the charge power of energy storage \( l \) at \( t \) the time, \( P_{dis,l,t} \) is discharge power of energy storage \( l \) at \( t \) time, \( \eta_{ch} \) is discharge efficiency of energy storage, \( \eta_{dis} \) is discharge efficiency of energy storage, \( G_{l,ESS} \) is the rated capacity of energy storage, and is generally not less than 10% of the rated photovoltaic capacity. \( \Delta t \) is the time interval—generally 1 h.

The charging and discharging power of the energy storage cannot exceed the maximum charging and discharging power, the energy storage cannot discharge and charge at the same time, and the state of charge cannot exceed the minimum and maximum value allowed by the user. Therefore, the setting constraints are as follows:

\[ 0 \leq P_{ch,l,t} \leq \omega_{ch,l,t} P_{ch,l,t,max} \]  \hspace{1cm} (5)

\[ 0 \leq P_{dis,l,t} \leq \omega_{dis,l,t} P_{dis,l,t,max} \]  \hspace{1cm} (6)

\[ \omega_{ch,l,t} + \omega_{dis,l,t} \leq 1 \]  \hspace{1cm} (7)

\[ SOC_{l,min} \leq SOC_{l,t} \leq SOC_{l,max} \]  \hspace{1cm} (8)

where \( \omega_{ch,l,t} \) and \( \omega_{dis,l,t} \) are the charging state and discharging state of energy storage \( l \) at \( t \) time, take 0 or 1, \( P_{ch,l,t,max} \) is the maximum charge power of energy storage \( l \) at \( t \) time, \( P_{dis,l,t,max} \) is the maximum discharge power of energy storage \( l \) at \( t \) time, \( SOC_{l,min} \) and \( SOC_{l,max} \) minimum and maximum charge states of energy storage \( l \).

In addition to the active power regulation ability of the energy storage, the energy storage inverter can carry out continuous dynamic reactive power compensation in the four-quadrant operation range by utilizing its spare capacity and combined with the power
factor operation range. The inverter constraint and power factor constraint of the energy storage reactive power compensation [31] are shown below:

\[-\sqrt{(S_{ESS,l})^2 - (P_{ch,l,t})^2} \leq Q_{ESS,l,t} \leq \sqrt{(S_{ESS,l})^2 - (P_{ch,l,t})^2} \]  
(9)

\[-\sqrt{(S_{ESS,l})^2 - (P_{dis,l,t})^2} \leq Q_{ESS,l,t} \leq \sqrt{(S_{ESS,l})^2 - (P_{dis,l,t})^2} \]  
(10)

\[-(P_{ch,l,t} + P_{dis,l,t}) \tan(\arccos(PF_{ESS,l,down})) \leq Q_{ESS,l,t} \leq (P_{ch,l,t} + P_{dis,l,t}) \tan(\arccos(PF_{ESS,l,up})) \]  
(11)

where \(Q_{ESS,l,t}\) is the reactive power of the energy storage inverter \(l\) at \(t\) the time, \(S_{ESS,l}\) is the rated capacity of the energy storage inverter \(l\), \(PF_{ESS,l,down}\) and \(PF_{ESS,l,up}\) the upper and lower limits of the energy storage rated power factor.

### 2.4. Tunable Ability to Single-Phase Photovoltaic and Energy Storage Considering Photovoltaic Permeability

To sum up, the controllable part of the single-phase photovoltaic and energy storage combination includes active power regulation and reactive power regulation. Assuming that the load demand remains unchanged, in the case of grid-connected single-phase optical storage, the active power of its junction point depends on the active power output of photovoltaic and the charge and discharge power of energy storage, as shown in the following formula:

\[P_{net,l,t} = P_{PV,l,t} - P_{ch,l,t} + P_{dis,l,t} \]  
(12)

where \(P_{net,l,t}\) is the active power flowing to the grid from its junction point of single-phase photovoltaic and energy storage \(l\) at the \(t\) time.

The reactive power of single-phase photovoltaic and energy storage joint node depends on the reactive power of the single-phase photovoltaic inverter and the reactive power of the energy storage system inverter, as shown in the following formula:

\[Q_{net,l,t} = Q_{PV,l,t} + Q_{ESS,l,t} \]  
(13)

where \(Q_{net,l,t}\) is the reactive power flowing to the grid from its junction point of single-phase photovoltaic and energy storage \(l\) at the \(t\) time.

For the definition of photovoltaic permeability, this paper defines the single-phase photovoltaic permeability of the distribution area as follows [32]:

\[\delta_s = \frac{S_{PV}}{\max_{load}} \times 100\% \]  
(14)

where \(S_{PV}\) is the total installed single-phase photovoltaic capacity in the distribution area, \(\max_{load}\) is the maximum active load in this area.

To simplify the calculation, assume the permeability is \(\delta_s\). The capacity of each single-phase photovoltaic is the same, and the single-phase photovoltaic is equally distributed to the access position. To simulate the randomness of the access position of single-phase photovoltaic, the random matrix is set to randomly generate the nodes and phases of single-phase photovoltaic access, so the number of single-phase photovoltaic at each position is:

\[n_{PV} = \delta_s \frac{\max_{load}}{S_{PV,iMZ}} \]  
(15)

To more conveniently represent the polymerization control of single-phase photovoltaic and energy storage in different positions, use two-dimensional coordinate points \((i, y)\) to describe the access locations of single-phase photovoltaic, \(i\) is the single-phase photovoltaic access node, \(y\) is single-phase photovoltaic access phase, and assume it accesses
$n_{PV}$ single-phase photovoltaics in $(i, y)$, so the controllable part of single-phase photovoltaic and energy storage is shown in the following equation:

$$\begin{aligned}
    P_{PV,ESS,i,y,t} &= \sum_{d=1}^{n_{PV}} P_{net,i,t} \\
    Q_{PV,ESS,i,y,t} &= \sum_{d=1}^{n_{PV}} Q_{net,i,t}
\end{aligned}$$

(16)

where $P_{PV,ESS,i,y,t}$ is the active power regulation ability to single-phase photovoltaic and energy storage and union dot in $(i, y)$ at the $t$ time, $Q_{PV,ESS,i,y,t}$ is the reactive power regulation ability to single-phase photovoltaic and energy storage and union dot $(i, y)$ at the $t$ time, $P_{net,i,t}$ is the active power flowing to the grid from its junction point of single-phase photovoltaic and energy storage $d$ in $(i, y)$ at the $t$ time, $Q_{net,i,t}$ is the reactive power flowing to the grid from its junction point of single-phase photovoltaic, and energy storage $d$ in $(i, y)$ at the $t$ time.

3. Consider Single-Phase Photovoltaic and Energy Storage Joint Regulation of the Three-Phase Unbalance Governance Model

3.1. Basic Framework

The three-phase unbalanced governance model that considers single-phase photovoltaic and energy storage joint regulation aims to fully tap the potential of a large number of single-phase photovoltaic and energy storage joint regulations in the distribution system and coordinate reactive power compensation equipment at the distribution network side. The optimization objective is to minimize the three-phase unbalance degree in the distribution area and the regulatory cost of photovoltaic and energy storage users. The three-phase unbalance degree of the power distribution system can be effectively reduced, the cost of user-side resources participating in the three-phase unbalanced governance can improve the economy of operation, and the renewable resources can be absorbed to improve the power quality of the power distribution system. Figure 2 is the schematic diagram of the strategy.

![Figure 2. Strategy diagram.](Image)
3.2. Objective Function

3.2.1. The Three-Phase Unbalance in the Distribution Area Is the Smallest

The three-phase current is taken as the analysis object of the three-phase unbalance of the distribution system. When the three-phase current is asymmetric, the three-phase current can be converted into zero-sequence, positive sequence, and negative sequence currents by the symmetric component method, as shown below:

\[
\begin{align*}
    I_{0,ij,t} &= \frac{1}{3} (I_{A,ij,t} + I_{B,ij,t} + I_{C,ij,t}) \\
    I_{1,ij,t} &= \frac{1}{3} (I_{A,ij,t} + aI_{B,ij,t} + a^2I_{C,ij,t}) \\
    I_{2,ij,t} &= \frac{1}{3} (I_{A,ij,t} + a^2I_{B,ij,t} + aI_{C,ij,t})
\end{align*}
\] (17)

where \( I_{A,ij,t}, I_{B,ij,t}, \) and \( I_{C,ij,t} \) refer to the current of A phase, B phase and C phase in the node at \( t \) time, \( I_{0,ij,t}, I_{1,ij,t}, \) and \( I_{2,ij,t} \) refer to the zero sequences, positive sequence, and negative sequence current corresponding to the three-phase current in \( i \) the node at \( t \) time, \( a \) is the twiddle factor, its value is \(-1/2+i\sqrt{3}/2\).

The definition of a three-phase unbalanced degree in \( i \) the node at \( t \) time is:

\[
\epsilon_{i,t} = \frac{I_{2,ij,t}}{I_{1,ij,t}}
\] (18)

where \( I_{2,ij,t} \) is the effective value of negative sequence current in \( i \) the node at \( t \) time, \( I_{1,ij,t} \) is the effective value of positive sequence current in \( i \) the node at \( t \) time.

To better describe the three-phase unbalance of the whole distribution area, this paper defines the three-phase unbalance of power distribution area as the sum of the three-phase unbalance degree of each node, the following formula is shown:

\[
\epsilon_{un,t} = \sum_{i=1}^{N} \epsilon_{i,t}
\] (19)

where \( N \) is the total number of nodes in the power distribution area.

Therefore, the objective function of the model is the minimum three-phase unbalance degree in the distribution area:

\[
\min f_1 = \epsilon_{un,t}
\] (20)

3.2.2. Single-Phase Photovoltaic and Energy Storage User Control Cost Is Minimal

Considering that subsidies are needed to call the photovoltaic user’s photovoltaic and energy storage equipment in the treatment of three-phase unbalance, the objective function of the photovoltaic user’s regulation cost is shown as follows:

\[
\min f_2 = \kappa \sum_{(i,j) \in M} (P_{PV,ESS,i,j,t} + Q_{PV,ESS,i,j,t})
\] (21)

where \( \kappa \) refers to the subsidies for distributed photovoltaic participation and \( M \) is the two-dimensional coordinate set of access locations of single-phase photovoltaic and energy storage.

In this paper, the linear weighting method is used to simplify the calculation of multiobjective optimization problems. Therefore, we obtain the total objective function as:

\[
\min F = k_1 \frac{f_1}{f_{1,max}} + k_2 \frac{f_2}{f_{2,max}}
\] (22)

\[
k_1 + k_2 = 1
\] (23)
where $k_1$ and $k_2$ are the weight of objective function $f_1$ and objective function $f_2$ in the actual situation, the power distribution department can set the corresponding weight according to the importance of governance objectives, $f_{1,\text{max}}$ is the three-phase unbalance degree of the distribution area when all single-phase photovoltaic power is connected at the $t$ time, and $f_{2,\text{max}}$ is the total cost of the single-phase photovoltaic active power output and inverter reactive power output when they are online.

3.3. Constraint Condition

3.3.1. Power Balance Constraint

Power flow constraints should be met in the governance process, including active power constraints and reactive power constraints, as shown below:

$$ P_{PV,ESS,i,y,t} - P_{d,i,y,t} = e^y \sum_{j=1}^{n} \sum_{\beta=A,B,C} (G^\beta_{ij} e^\beta_{ij} - B^\beta_{ij} f^\beta_{ij}) + f^y \sum_{j=1}^{n} \sum_{\beta=A,B,C} (G^\beta_{ij} e^\beta_{ij} + B^\beta_{ij} f^\beta_{ij}) $$  \hspace{1cm} (24)

where $P_{d,i,y,t}$ is the active power of load in the node $i$ of $y$ phase at the $t$ time, $Q_{d,i,y,t}$ is the reactive power of load in the node $i$ of $y$ phase at the $t$ time, $G^\beta_{ij}$ and $B^\beta_{ij}$ are the conductance and susceptance between the node $i$ of $y$ phase and node $j$ of $\beta$ phase, $Q_{SV,C,i,y,t}$ is the reactive power of SVC in the node $i$ of $y$ phase at the $t$ time, $P_{PV,ESS,i,y,t}$ is the active power of single-phase photovoltaic and energy storage in the node $i$ of $y$ phase at the $t$ time, and $Q_{PV,ESS,i,y,t}$ is the reactive power of single-phase photovoltaic and energy storage in the node $i$ of $y$ phase at the $t$ time.

3.3.2. The Constraint of SVC

The reactive power compensation quantity constraint of the SVC is shown as follows:

$$ Q_{SV,C,\text{min}} \leq Q_{SV,C,m,y,t} \leq Q_{SV,C,\text{max}} $$  \hspace{1cm} (26)

where $Q_{SV,C,\text{min}}$ and $Q_{SV,C,\text{max}}$ are the minimum and maximum output reactive power of SVC, $Q_{SV,C,i,y,t}$ is the reactive power of SVC at the $t$ time.

3.3.3. The Constraint of Voltage Deviation

To ensure that the voltage deviation of the distribution network is within a certain range, the constraint conditions are set as follows

$$ V_{\text{min}} \leq \sqrt{(V_{ij}^y)^2} \leq V_{\text{max}} $$  \hspace{1cm} (27)

where $V_{ij}^y$ is the voltage in the node $i$ of $y$ phase at the $t$ time, $V_{\text{min}}$ and $V_{\text{max}}$ are the maximum voltage and minimum voltage; generally, the voltage deviation of the 10 kV distribution system should be kept within 7% [33].

3.4. The Solution Process Based on the JAYA Optimization Algorithm

The JAYA algorithm [34] is a start-element optimization algorithm proposed by R. Venkata Rao with the advantages of running without parameters, a fast solving speed, and does not fall into the local optimal solution. It is based on the principle of continuous improvement: the individual is constantly close to the excellent individual while constantly away from the poor individual, and then constantly improves the quality of the solution. The population is initialized, and new solutions are obtained through iterative evolution, as follows:

$$ X_0(:, j_a) = \text{min}(j_a) + (\text{max}(j_a) - \text{min}(j_a)) \cdot \text{rand(pop, 1)} $$  \hspace{1cm} (28)
\[ X'_{j_0,k_{id}} = X_{j_0,k_{id}} + r_{1,j_0,k_{id}} (X_{j_0,\text{best}_{id}} - |X_{j_0,k_{id}}|) - r_{2,j_0,k_{id}} (X_{j_0,\text{worst}_{id}} - |X_{j_0,k_{id}}|) \] (29)

where \( X_0(:,j_{id}) \) is the initial population of \( j_{id} \) variable, \( \text{mini}(j_{id}) \) is the lower bound of \( j_{id} \) variable, \( \text{maxi}(j_{id}) \) is the upper bound of \( j_{id} \) variable, \( \text{rand}(\text{pop},1) \) is used for generate a pop random number between 0 and 1, \( \text{pop} \) is the population number, \( X_{j_0,k_{id}} \) is the \( j \) variable of \( k \) the individual in \( i \) iteration, \( X_{j_0,\text{best}_{id}} \) is the \( j \) variable of the best individual in \( i \) iteration, \( X_{j_0,\text{worst}_{id}} \) is the \( j \) variable of the worst individual in \( i \) iteration, \( |X_{j_0,k_{id}}| \) is the absolute value of \( X_{j_0,k_{id}} \), \( r_{1,j_0,k_{id}} \) and \( r_{2,j_0,k_{id}} \) are the random number between 0 and 1, \( X'_{j_0,k_{id}} \) is the updated value of \( X_{j_0,k_{id}} \).

The solving steps of the model are shown in Figure 3:

**Figure 3.** The solving steps of the model.

1. The input data includes the single-phase photovoltaic output curve, single-phase photovoltaic access position, SVC access position, and system power impedance matrix.
(2) Judge the three-phase unbalance degree of each node at time $t$: if it exceeds the limit range of the three-phase unbalance degree allowed by the power distribution system, the governance strategy proposed in this paper will be started. Otherwise, there is no need to conduct governance, and the system will run to meet the requirements.

(3) Initialization of parameters of the governance strategy model: set the number of variables, population number and the number of iterations, then initialize the population, and calculate the best and worst solutions of the objective function $F$ in the population.

(4) Optimization iteration of the governance strategy model: the best and worst solutions of the objective function $F$ in the population are modified. If the modified solution is larger than the previous solution, the previous solution is received and replaced; otherwise, the previous solution is maintained.

(5) Judge whether the number of iterations meets the requirements: if it is greater than the set number of iterations, the control scheme of each SVC and each single-phase optical storage under the optimized output time $t$ will be finished for three-phase unbalanced governance; if it is less than the set number of iterations, it will return to step (4) to continue the iteration.

4. Analysis of Examples

4.1. Parameter Setting

Take the IEEE33-node power distribution system shown in Figure 4 as an example and refer to the literature [35] for specific line parameters. Assume that the access locations of the single-phase photovoltaic and energy storage in the IEEE33-node distribution system are shown in Table 1, and that two three-phase static reactive power compensation SVC that can be adjusted in separate phases are respectively connected to No12 and No25. The photovoltaic output curve on typical sunny days is shown in Figure 5, and other parameters used in the calculation example are shown in Table 2.

![Figure 4. The 33-node power distribution system.](image)

<table>
<thead>
<tr>
<th>Location</th>
<th>(Node, Phase)</th>
<th>Location</th>
<th>(Node, Phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(7, C)</td>
<td>6</td>
<td>(18, C)</td>
</tr>
<tr>
<td>2</td>
<td>(9, C)</td>
<td>7</td>
<td>(19, B)</td>
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</tr>
<tr>
<td>5</td>
<td>(16, B)</td>
<td>10</td>
<td>(30, C)</td>
</tr>
</tbody>
</table>
Figure 5. Photovoltaic output curve on a typical sunny day.

Table 2. Other parameter settings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>population size</td>
<td>100</td>
<td>$\eta_{\text{dis}} / \eta_{\text{ch}}$</td>
<td>0.9</td>
</tr>
<tr>
<td>iterations</td>
<td>500</td>
<td>$G_{\text{ESS}}$</td>
<td>5 kW</td>
</tr>
<tr>
<td>$k_1$</td>
<td>0.5</td>
<td>$P_{\text{ch},j,\text{max}}$</td>
<td>2 kW</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.5</td>
<td>$P_{\text{dis},j,\text{max}}$</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>$Q_{\text{SVC},\text{min}}$</td>
<td>0 kvar</td>
<td>$S_{\text{SVC,}i,\text{min}}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$Q_{\text{SVC,}j,\text{max}}$</td>
<td>300 kvar</td>
<td>$S_{\text{SVC,}j,\text{max}}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$S_{\text{PV,}j}$</td>
<td>8 kW</td>
<td>$S_{\text{ESS,}j}$</td>
<td>5 kW</td>
</tr>
<tr>
<td>$S_{\text{PVc,}j}$</td>
<td>9.6 kW</td>
<td>$P_{\text{ESS,}j,\text{down}}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$P_{\text{load}}$</td>
<td>3635 kW</td>
<td>$P_{\text{ESS,}j,\text{up}}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.4 yuan</td>
<td>$M_Z$</td>
<td>10</td>
</tr>
</tbody>
</table>

4.2. Discussion

4.2.1. The Influence of Different Single-Phase Photovoltaic Permeability on the Unbalance Degree of Three-Phase

Taking into account the limitations of where photovoltaic panels can be placed in the city, it is assumed that single-phase photovoltaic capacity permeability increases from 5% to 30% at 5% intervals. It is assumed that the photovoltaic is connected to the position shown in Table 1 at different scales under different permeability, and the load of each node remains unchanged. Based on the three-phase push-back substitution method [36], the three-phase unbalance degree of the IEEE33 example system in the power distribution area at different periods under different photovoltaic permeability is calculated, as shown in Figure 6.

Figure 6 shows that the three-phase unbalance degree is increased from 8 to 14, decreased from 15 to 18, and other times remain unchanged. Because the photovoltaic output increases and then decreases with time, when the photovoltaic output is the highest at noon, the three-phase unbalance degree is the highest in the distribution area. With the increase in single-phase photovoltaic permeability, the three-phase unbalance of power distribution system obviously increases. Therefore, it is necessary to explore the regulation
ability of single-phase photovoltaic and energy storage under different permeabilities and solve the problem of three-phase unbalance.

![Image](image_url)

**Figure 6.** Three-phase unbalanced degree of distribution area at a different time under different permeability.

4.2.2. Effect Analysis of Treating Three-Phase Unbalance under Different Single-Phase Photovoltaic Permeability Scenarios

To verify the effectiveness of the strategy proposed in this paper, three permeability scenarios are set, representing low, medium, and high permeability scenarios, respectively. Scenario 1: 10% permeability; scenario 2: 20% permeability; and scenario 3: 30% permeability.

In Figure 7, it can be seen that before the governance, the three-phase unbalance degree of nodes 13, 17 and 20 at 12 are 0.18, 0.21 and 0.22, respectively—they are more than 0.15, which is required from the normal operation of a distribution network [2]. This is because the photovoltaic permeability in scenario 1 is low, and the influence on the three-phase unbalance of the distribution network is small. After governance, which is proposed by this paper, the three-phase unbalance degree of nodes 13, 17 and 20 at 12 reduce to 0.08, 0.05, and 0.03, respectively, which meet the operation requirements of the distribution network. In scenario 1, the real-time regulation schemes of the single-phase photovoltaic and energy storage and the static reactive power compensation device are shown in Figures 8 and 9. It can be found that when the three-phase unbalance degree of nodes in the distribution network does not exceed 0.15 at 0–9 and 15–24 points, there is no active and reactive power output scheme for single-phase optical storage at each position, and the static reactive power device does not start reactive power scheme. When the three-phase unbalance degree of nodes exceeds 0.15 from 10 o’clock, single-phase photovoltaic and energy storage and static reactive power compensation devices start to work.

In Figure 10, it can be seen that before the governance, the three-phase unbalance degrees of nodes 11, 12, 13, 17, and 20 at 12 are 0.25, 0.28, 0.34, 0.46, and 0.50, respectively. The three-phase unbalance degree in scenario 2 is bigger than scenario 1, because the photovoltaic permeability in scenario 2 is higher than scenario 1. After governance which is proposed by this paper, the three-phase unbalance degree of nodes 11, 12, 13, 17 and 20 at 12 reduce to 0.07, 0.07, 0.08, and 0.09, respectively, which meet the operation requirements of the distribution network. However, some of the nodes’ three-phase unbalance degrees cannot meet the requirement of less than 0.15, such as nodes 19, 20 and 21 at 13. In scenario 2, the real-time regulation schemes of the single-phase photovoltaic and energy storage and the static reactive power compensation device are shown in Figures 11 and 12. It can be found that the adjustability of single-phase photovoltaic and energy storage in scenario 2 is bigger than in scenario 1.
The three-phase unbalance degree in scenario 2 is bigger than scenario 1, because the photovoltaic and energy storage in scenario 2. When the three-phase unbalance degree of nodes exceeds 0.15 from 10 o’clock, single-phase photovoltaic and the static reactive power device does not start reactive power scheme. When the three-phase unbalance degree of nodes 11, 12, 13, 17, and 20 at 12 are 0.25, 0.28, 0.34, 0.46, and 0.50, respectively.

In Figure 7, it can be seen that before the governance, the three-phase unbalance degree of each node at each time before (left) and after (right) governance in scenario 1.

Figure 8. Active power (left) and reactive power (right) scheme for single-phase photovoltaic and energy storage in scenario 1.

Figure 9. Reactive power output scheme of SVC in scenario 1.

Figure 10. Three-phase unbalance degree of each node at each time before (left) and after (right) governance in scenario 2.
The three-phase unbalance degree in scenario 2 is bigger than in scenario 1. After governance, which is proposed by this paper, the three-phase unbalance degree of most nodes decreases; for example, the three-phase unbalance degree of node 13 at 12 goes from 0.49 to 0.07, the three-phase unbalance degree of node 17 at 12 goes from 0.55 to 0.06, and so on. In scenario 3, the real-time regulation schemes of the single-phase photovoltaic and energy storage and the static reactive power compensation device are shown in Figures 14 and 15. It can be found that the adjustability of single-phase photovoltaic and energy storage in scenario 3 is bigger than in scenario 1 and scenario 2.

Figure 11. Active power (left) reactive power (right) scheme for single-phase photovoltaic and energy storage in scenario 2.

Figure 12. Reactive power output scheme of SVC in scenario 2.

Figure 13 shows that before the governance, the three-phase unbalance degree of most nodes is more than 0.15 from 9 to 17, such as nodes 12, 13, 18, 20, 21 and so on. The distribution network is in a state of serious unbalance because the photovoltaic permeability in scenario 3 is the highest among the three scenarios. After governance, which is proposed by this paper, the three-phase unbalance degree of most nodes decreases; for example, the three-phase unbalance degree of node 13 at 12 goes from 0.49 to 0.07, the three-phase unbalance degree of node 17 at 12 goes from 0.55 to 0.06, and so on. In scenario 3, the real-time regulation schemes of the single-phase photovoltaic and energy storage and the static reactive power compensation device are shown in Figures 14 and 15. It can be found that the adjustability of single-phase photovoltaic and energy storage in scenario 3 is bigger than in scenario 1 and scenario 2.

Figure 13. Three-phase unbalance degree of each node at each time before (left) and after (right) governance in scenario 3.
Figure 13 shows that before the governance, the three-phase unbalance degree of most nodes is more than 0.15 from 9 to 17, such as nodes 12, 13, 18, 20, 21 and so on. The distribution network is in a state of serious unbalance because the photovoltaic permeability in scenario 3 is the highest among the three scenarios. After governance, which is proposed by this paper, the three-phase unbalance degree of most nodes decreases; for example, the three-phase unbalance degree of node 13 at 12 goes from 0.49 to 0.07, the three-phase unbalance degree of node 17 at 12 goes from 0.55 to 0.06, and so on. In scenario 3, the real-time regulation schemes of the single-phase photovoltaic and energy storage and the static reactive power compensation device are shown in Figures 14 and 15. It can be found that the adjustability of single-phase photovoltaic and energy storage in scenario 3 is bigger than in scenario 1 and scenario 2.

Figure 13. Three-phase unbalance degree of each node at each time before (left) and after (right) governance in scenario 3.

Figure 14. Active power (left) reactive power (right) scheme for single-phase photovoltaic in scenario 3.

Figure 15. Reactive power output scheme of SVC in scenario 3.

4.2.3. Comparative Analysis under Different Strategies

To verify the effectiveness and economy of single-phase photovoltaic and energy storage joint regulation in the treatment of three-phase unbalance, four groups of strategies are set for comparative analysis, assuming that the single-phase photovoltaic permeability is 10%.

- Strategy 2: SVC, single-phase photovoltaic active power and its corresponding inverter reactive power output participate in governance.
- Strategy 3: Joint regulation and management of SVC and single-phase photovoltaic and energy storage, but only target $f_1$ is considered.
- Strategy 4: Joint regulation and management of SVC and single-phase optical storage, but considering target $f_1$ and $f_2$, namely, the strategy proposed in this paper.

The comparison results of the four groups are shown in Table 3. The three-phase unbalance degree of the daily power distribution area is the sum of the three-phase unbalance degree of the 24 h power distribution area, and the adjustment cost of the daily photovoltaic and energy storage user is the sum of the adjustment cost of the 24 h photovoltaic user.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Three-Phase Unbalance of the Daily Distribution Area</th>
<th>Daylight Storage User Control Cost/Yuan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.87</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>25.29</td>
<td>1320.58</td>
</tr>
<tr>
<td>3</td>
<td>26.86</td>
<td>1314.00</td>
</tr>
<tr>
<td>4</td>
<td>27.05</td>
<td>1013.22</td>
</tr>
</tbody>
</table>
It can be seen from Table 3 that in strategy 1, if only the static reactive power compensation device participates in the treatment of three-phase unbalance, the three-phase unbalance degree of the daily power distribution area is still at a high level; in strategy 2, if only SVC, single-phase photovoltaic active power, and the reactive power of its corresponding inverter participate in the treatment of three-phase unbalance, the three-phase unbalance degree of the daily power distribution area is reduced compared to strategy 1. Compared to strategy 2, strategy 3 increases the three-phase unbalance degree in the distribution area, but it reduces the regulation cost for users of photovoltaic and energy storage. This is because the joint regulation of single-phase photovoltaic and energy storage improves the adjustable range of the energy flowing from the single-phase photovoltaic node to the grid, so the output energy of the photovoltaic and energy storage node can be adjusted and reduced. Strategy 4 also takes into account the three-phase unbalance degree of the power distribution area and the regulation cost of photovoltaic users. The results show that although the three-phase unbalance degree of the daily power distribution area increases by 0.19 compared to strategy 3, the three-phase unbalance degree of most node still meets the operation requirements, and the regulation cost of photovoltaic and energy storage is further reduced by CNY 301. Therefore, the distribution area three-phase unbalance problem is effectively controlled and considers the economy of governance.

5. Conclusions

This paper proposes a three-phase unbalanced treatment strategy for the distribution network, which considers the joint regulation ability of single-phase photovoltaic and energy storage and the regulation ability of the reactive power compensation device. Firstly, the joint regulation ability of single-phase photovoltaic and energy storage under different photovoltaic permeability is analyzed, and it can be found that the active and reactive power of single-phase photovoltaic and energy storage can be fully invoked in the treatment process. Secondly, the three-phase power optimization model is constructed to minimize three-phase unbalance degree and regulation cost, and the JAYA optimization algorithm is used to solve the model. According to the comparison of the four groups’ strategies, it can be found that the joint regulation ability of single-phase photovoltaic and energy storage and reactive power compensation device is better than other strategies. The strategy proposed by this paper can effectively reduce the three-phase unbalance degree of the distribution network and optimizes regulation cost compared with other strategies; therefore, this strategy has commercial possibility. In the future, the strategy proposed in this paper can be better applied in places with high photovoltaic permeability and provides some meaningful governance solutions for the three-phase unbalance problem. In further research, this strategy can be considered in combination with commutation technology.

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References


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