

Energy Storage-Based Power Control Method for Power Quality Control and Loss Reduction in Distribution Substation with PV

1st Chuanwen Zhang

College of Electrical and Information Engineering
Hunan University
Changsha, China
zcw0426@hnu.edu.cn

2nd Yong Li*

College of Electrical and Information Engineering
Hunan University
Changsha, China
yongli@hnu.edu.cn

3rd Senao Liu

College of Electrical and Information Engineering
Hunan University
Changsha, China
liusenao@hnu.edu.cn

4th Guoxin Sun

College of Electrical and Information Engineering
Hunan University
Changsha, China
sunguoxin@hnu.edu.cn

Abstract—In order to improve power quality and reduce losses in distribution substations with PV, this paper proposes an energy storage-based power control method. Firstly, this paper introduces the topology and control methods of the energy storage-based power control system. Secondly, based on the active power of the substation and the state of charge of the energy storage batteries, the system states and operating modes are classified, thereby determining the output commands for the energy storage-based power control system under different modes. Finally, a simulation model of the energy storage-based power control system is established to verify the effectiveness of the proposed method.

Keywords—component; power quality, reduce losses, distribution substation, PV, energy storage-based power control, system states, operating modes

I. INTRODUCTION

With the large-scale integration of distributed photovoltaic systems into distribution transformer districts, the installed capacity of these systems has far exceeded the load of the districts. Excess electricity is fed back to the upstream grid via distribution lines and transformers. Furthermore, the connection of distributed PV systems as single-phase loads exacerbates three-phase imbalance. This reverse power flow and three-phase imbalance lead to increased losses in the distribution network [1]–[3].

Currently, the primary measures for mitigating distribution network losses include raising operating voltage, providing reactive power compensation, balancing three-phase loads, using high-efficiency distribution transformers, and network restructuring. Reference [4] addresses the issue of reactive power control failure in distributed energy systems by maintaining system voltage quality through fault scenario analysis and the use of dynamic reactive power compensation devices. Reference [5] proposes a distributed control strategy that utilizes the available reactive power of DRES as the primary means of regulation, with the aim of regulating voltage in unbalanced low-voltage distribution networks and maintaining the network voltage within permissible limits. Reference [6] proposes a point-to-point data sharing method between single-phase PV inverters, enabling the inverters to collaboratively regulate reactive power injection, thereby achieving coordinated voltage regulation and suppression of

voltage imbalance in the distribution network. Reference [7] proposes a line-impedance-based positive- and negative-sequence voltage compensation strategy, which enhances the system's fault-ride-through capability by controlling the positive- and negative-sequence voltages and currents of three-phase, three-wire inverters in the synchronous reference frame. However, the aforementioned measures have proven ineffective in addressing the issue of increased network losses caused by reverse power flow in PV substations.

The continuous development of energy storage technology has provided new solutions to address issues such as high network losses and exacerbated three-phase imbalance in distribution substations caused by the large-scale integration of PV systems. Energy storage systems possess bidirectional regulation capabilities to store and release electrical energy, enabling flexible energy management based on the actual needs of distribution substations. Reference [8] proposes an optimization method for the coordinated operation of PV inverters and battery energy storage systems (BESS), whereby PV inverters inject active power during periods of PV generation and provide reactive power compensation during other periods, whilst the BESS is used to store surplus PV power and release it during periods of low or no PV generation; this method can significantly reduce energy losses. Reference [9] proposes an energy control method based on optimal power flow and a power flow-based rule-based method, with the aim of reducing operational and maintenance costs, losses, and voltage fluctuations in unbalanced distribution networks. Reference [10] proposes a two-stage energy storage system loss reduction method based on loss-sensitive factors, with the aim of reducing energy losses in distribution networks; this method significantly reduces line losses by rationally configuring the charging and discharging power and timing of the energy storage system. Reference [11] proposes a dynamic optimal active power dispatch model for single-phase PV units and BESS, enabling dynamic optimization of energy storage system dispatch to effectively reduce energy losses in unbalanced systems and improve voltage quality. Reference [12] proposes an optimization method utilizing existing residential battery storage capacity, employing a particle swarm algorithm to determine optimal charge and discharge

commands, thereby effectively reducing power losses caused by the integration of PV and electric vehicles.

In this paper, an energy storage-based power control method is proposed for power quality improvement and loss reduction in distribution substations with photovoltaic, with the aim of addressing the aforementioned issues. Firstly, the topology and control methods of the energy storage-based power control system are introduced; secondly, different operating states of the distribution transformer are classified based on load power and the state of charge (SOC) of the energy storage batteries; finally, the effectiveness of this method in improving power quality and reducing losses is verified through simulation using actual operational data from a distribution substation with PV.

II. TOPOLOGY AND CONTROL METHODS

A. Topology

The control system is shown in Figure 1. The distributed PV system is connected to the distribution network via a low-voltage grid connection, whilst the energy storage-based power control device is connected to the secondary side of the distribution transformer. The installed capacity of distributed PV is large relative to the small electricity load capacity, and the peak electricity consumption of residential loads is not synchronized with the peak power generation of distributed PV. The daily load curve exhibits characteristics of peak electricity consumption in the morning and evening, and PV power generation at midday being transmitted over long-distance lines to the upstream 10 kV grid. These operational characteristics lead to issues such as severe overloading of distribution transformers and significant power losses. Consequently, this paper proposes an energy storage-based power control method for improving power quality and reducing losses in distribution substations with PV.

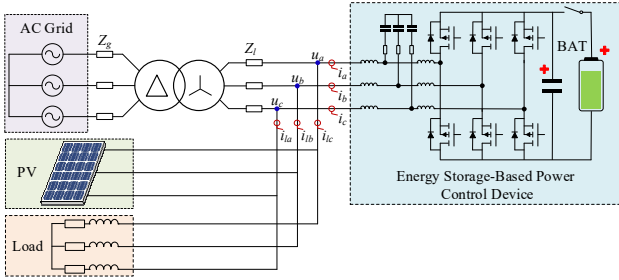


Figure 1. Topology of energy storage-based power control system

B. Control methods

As shown in Figure 2, the control system uses voltage u_{abc} and current i_{labc} sensors to collect real-time data on the secondary-side voltage and current of the distribution transformer in the feeder area, the output current of the control unit, and the SOC of the energy storage battery. The compensation control strategy identifies the current operating state of the distribution substation based on the active power and SOC value, and calculates the corresponding active, reactive and three-phase imbalance compensation commands. The current inner-loop controller employs Proportional-Integral-Resonant (PIR) control, which involves connecting a PR controller in parallel with the existing PI controller to achieve beat-free control of both the positive-sequence DC component and the negative-

sequence double-frequency oscillatory component simultaneously.

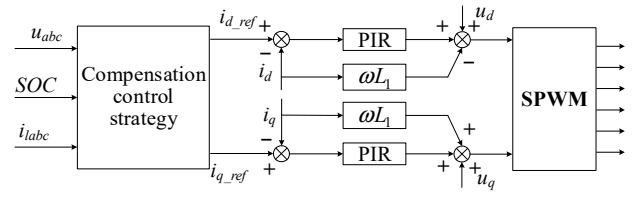


Figure 2. Control methods of energy storage-based power control system

III. COMPENSATION CONTROL STRATEGY

As shown in Figure 3, when the SOC of the energy storage battery approaches its upper or lower limits, the battery voltage undergoes significant fluctuations. The battery voltage may exceed the operating voltage range of the bidirectional DC/AC converter, thereby affecting the converter's normal operation. To ensure the converter operates normally, the battery's SOC can be divided into four operating zones: the over-discharge range $[0, SOC_{min}]$, the identification and correction range $[SOC_{min}, SOC_{low}]$, the optimal operating range $[SOC_{low}, SOC_{max}]$, and the over-charge range $[SOC_{max}, 100]$. When the battery is in the over-discharge zone, the discharge power must be corrected to prevent excessive discharge and extend the battery's lifespan. Therefore, a discharge correction factor is introduced as:

$$k_{SOC} = \begin{cases} 1, & SOC \geq SOC_{low} \\ \frac{1}{1 + e^{\left(\frac{10-20}{SOC_{low}-SOC_{min}} (SOC - SOC_{min}) \right)}}, & SOC_{min} \leq SOC < SOC_{low} \\ 0, & SOC < SOC_{min} \end{cases} \quad (1)$$

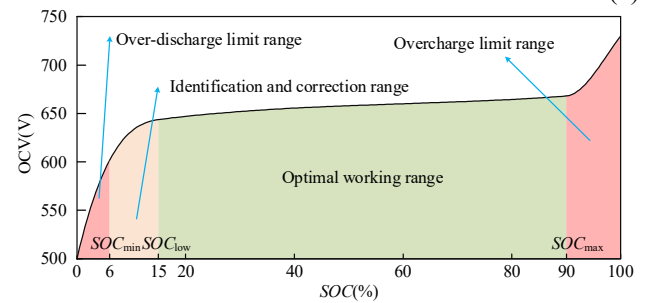


Figure 3. Classification of working ranges for energy storage batteries

As shown in Figure 4, the operating state of a transformer district can be divided into three distinct states: the peak reverse power flow state $[-\infty, P_L]$, the reasonable load factor state $[P_L, P_H]$, and the peak power consumption state $[P_H, \infty]$. When the substation is in the peak reverse power flow state, reverse peak shaving is performed; when the substation is in the peak power consumption state, forward peak shaving is performed; and when the substation is in the reasonable load factor state, power compensation is performed.

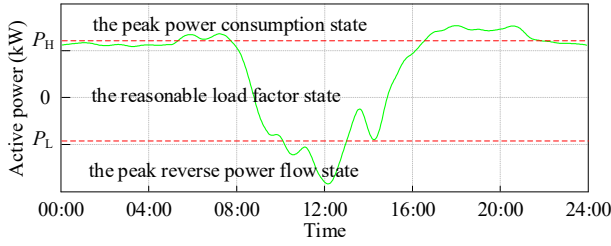


Figure 4. Classification of operating state for distribution substation

This paper selects the active power of the substation and the SOC of the energy storage battery as classification variables, dividing the system operating states into seven categories. Furthermore, the operating modes of the control device under different system operating states are determined. When the active power of the substation is lower than the reverse peak shaving setpoint and the battery SOC is lower than the charging upper limit setpoint, the control device charges according to the instructions issued by the compensation control strategy, which is defined as the reverse peak shaving mode; When the active power of the feeder zone exceeds the forward peak shaving setpoint and the battery SOC is above the discharge lower limit setpoint, the control device discharges according to the instructions issued by the compensation control strategy. When the battery SOC falls below the discharge warning setpoint, the system reduces the discharge power appropriately to prevent overcharging of the battery; this is defined as the forward peak shaving mode; When the active power of the feeder zone falls between the forward peak shaving and reverse peak shaving setpoints and the battery SOC is above the discharge lower limit setpoint, or when the load active power is below the reverse peak shaving setpoint and the battery SOC is above the charging upper limit setpoint, the control device performs reactive power and three-phase imbalance compensation to fully utilize the converter's capacity; this is defined as the power quality control mode; In all other states, the control device remains inactive; this is defined as the idle mode.

In summary, the system modes and state classifications are shown in Table I. In the table, P_{load} represents the active power of the load, P_H is the forward peak shaving setpoint, and P_L is the reverse peak shaving setpoint; SOC_{min} , SOC_{low} , and SOC_{max} are the SOC threshold values within the operating range of the energy storage battery.

TABLE I. CLASSIFICATION OF DISTRIBUTION TRANSFORMER OPERATION STATUS

Mode	State	Power	SOC
Reverse peak shaving	①	$P_{load} \leq P_L$	$SOC \leq SOC_{max}$
Forward peak shaving	②	$P_{load} > P_H$	$SOC > SOC_{low}$
	③	$P_{load} > P_H$	$SOC_{min} < SOC \leq SOC_{low}$
Power Quality Control	④	$P_L < P_{load} \leq P_H$	$SOC > SOC_{min}$
	⑤	$P_{load} \leq P_L$	$SOC > SOC_{max}$
Idle	⑥	$P_L < P_{load} \leq P_H$	$SOC \leq SOC_{min}$
	⑦	$P_{load} > P_H$	$SOC \leq SOC_{min}$

Based on the classification into seven states and four modes presented in Table 1, and in conjunction with the relationship between load dispersion and power loss

described above, we will analyze the compensation values of the control device under different modes.

A. Reverse peak shaving mode

In this mode, the distribution substation is experiencing peak reverse power flow. To reduce the load factor of the distribution transformers, minimize the duration of severe overloading, and ensure the safe and efficient operation of the distribution network, the current compensation values for the control device are set as follows:

$$\begin{cases} i_d^* = \frac{2}{3U_d} (P_{load} - P_L) \\ i_q^* = -\frac{2}{3U_d} Q_{load} \end{cases} \quad (2)$$

where U_d represents the amplitude of d-axis component of the voltage.

B. Forward peak shaving mode

In this mode, the distribution substation is operating under peak load conditions, and the batteries are in their optimal operating range or overcharge range. To reduce the peak-to-off-peak difference and ensure a balanced charge-discharge cycle for the batteries, a discharge correction factor is introduced. The current compensation values for the control device are set as follows:

$$\begin{cases} i_d^* = \frac{2}{3U_d} \min(P_{load} - P_H, k_{SOC} S_N) \\ i_q^* = -\frac{2}{3U_d} Q_{load} \end{cases} \quad (3)$$

where S_{PCS} represents the rated capacity of the converter.

C. Power Quality Control Mode

In this mode, the distribution substation operates at a reasonable load factor. By utilizing the idle capacity of the power converter for power quality improvement, the power supply quality and operational efficiency of the distribution network are enhanced. The current compensation values for the control device are set as follows:

$$\begin{cases} i_d^* = i_{d-} \\ i_q^* = \frac{2}{3U_d} Q_{load} + i_{q-} \end{cases} \quad (4)$$

where i_{d-} represents the d-axis component of the load current and the negative-sequence current, i_{q-} represents the q-axis component of the load current and the negative-sequence current.

D. Idle Mode

In this mode, the battery's SOC is low. Even when the inverter connected to the battery is in a state of no discharge, the battery will still discharge on its own and lose charge; furthermore, battery discharge accelerates when the inverter performs reactive power compensation. To prevent prolonged over-discharge of the battery, the current compensation value of the control device is set as follows:

$$\begin{cases} i_d^* = 0 \\ i_q^* = 0 \end{cases} \quad (5)$$

In summary, the state and mode classifications for the compensation control strategy of the energy storage-based power control device are shown in Figure 5.

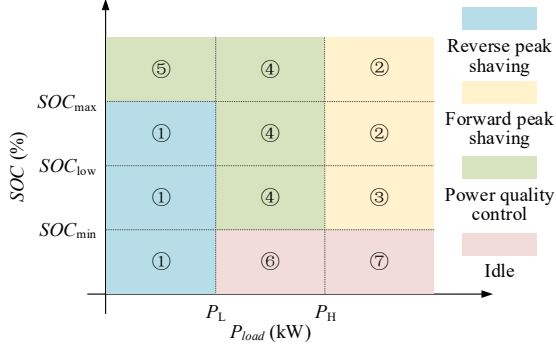


Figure 5. Classification of compensation control strategy states and modes

IV. SIMULATION RESULTS

Using actual operational data from a specific photovoltaic substation as an example, this paper develops a simulation model in conjunction with the proposed energy storage-based power control method.

The simulation parameters are shown in Table II.

TABLE II. SIMULATION MODEL PARAMETERS

Variable	value	Variable	value
SOC_{min}	6%	P_H	8.2kW
SOC_{low}	15%	S_{TN}	100kVA
SOC_{max}	90%	ΔP_0	0.22kW
P_L	-77kW	ΔP_K	1.5kW

Figure 6 illustrates the compensation performance in reverse peak shaving mode, with load conditions of $P_{load} = -105$ kW and $Q_{load} = 30$ kVar. The control device was activated at $t = 0.25$ s. As shown in Figure 6, after the control device was activated, the active power on the grid side was reduced to the reverse peak shaving setpoint, and the reactive power was reduced to zero.

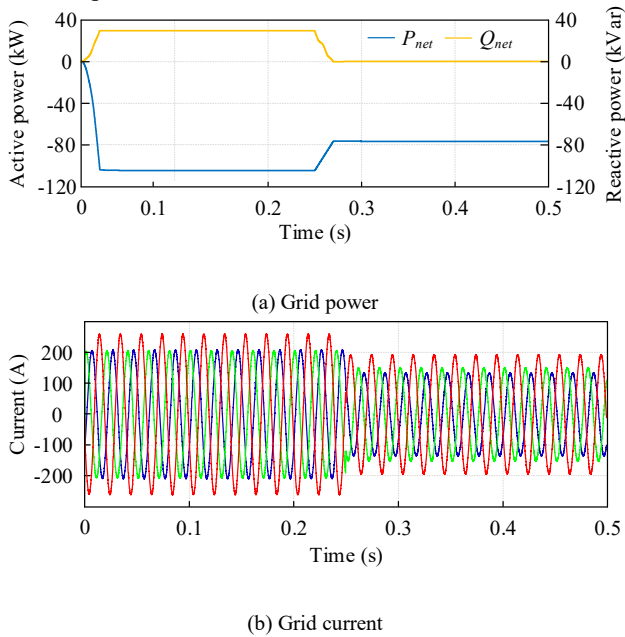


Figure 6. Compensation effect of reverse clipping mode

Figure 7 shows the compensation results under forward peak shaving mode, with load conditions of $P_{load} = 25$ kW and $Q_{load} = 30$ kVar. The control device was activated at $t = 0.25$ s. As shown in Figure 7, after the control device was activated, in State ②, the grid-side active power was reduced to the forward peak shaving setpoint, and the reactive power was reduced to zero; In State ③, the grid-side reactive power is reduced to zero. However, because the battery is operating in the over-discharge region, its output power is limited by the discharge correction factor, resulting in a certain reduction in active power, which remains slightly greater than the forward peak-shaving setpoint.

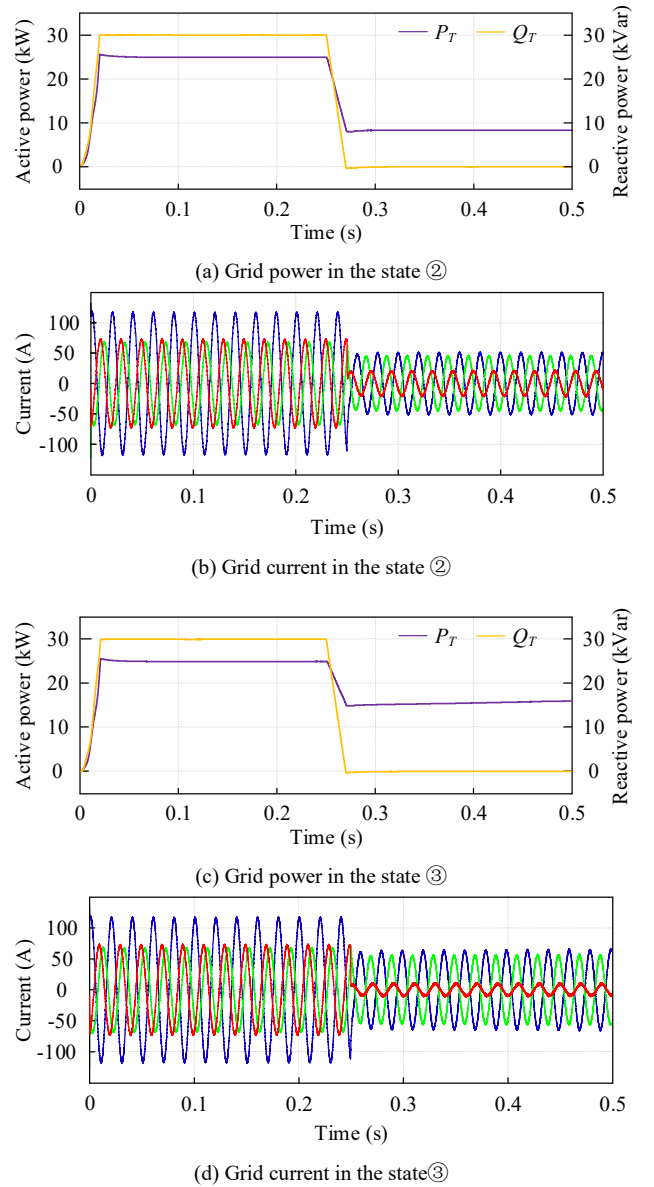
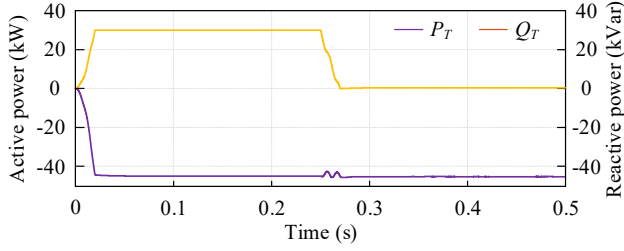


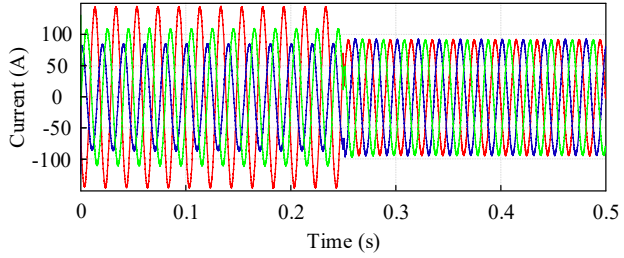
Figure 7. Compensation effect of positive peak shaving mode

Figure 8 shows the compensation results under the power quality control mode, where the load conditions for state ④ are $P_{load} = -45$ kW and $Q_{load} = 30$ kVar; the load conditions for state ⑤ are $P_{load} = -105$ kW and $Q_{load} = 30$ kVar. The control device was activated at $t = 0.25$ s. As shown in Figure 8, after the control device was activated,

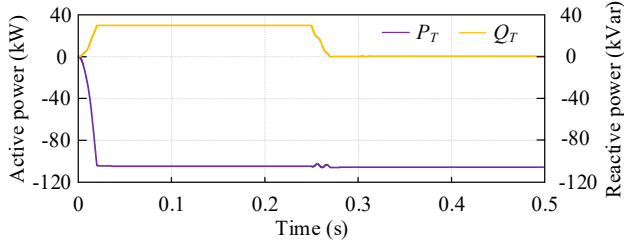
the active power remained essentially constant, the grid side reactive power was reduced to zero, and the three-phase imbalance in the grid-side current was corrected.



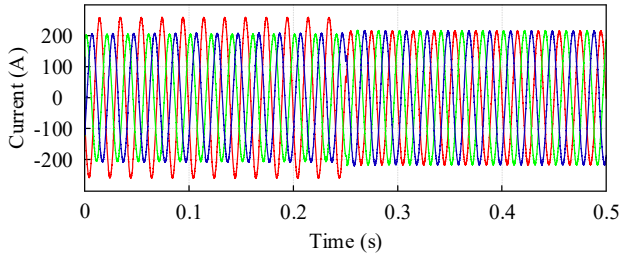
(a) Grid power in the state ④



(b) Grid current in the state ④



(c) Grid power in the state ⑤



(d) Grid current in the state ⑤

Figure 8. Compensation effect of electrical energy governance mode

In idle mode, to prevent over-discharge of the storage battery, the control device remains inactive, and the grid side current imbalance and power loss remain constant.

As shown in Table 3, with the exception of idle mode, the control device reduces losses in distribution sub-areas to varying degrees in all other modes. In states ①, ②, and ③—that is, in reverse peak shaving and forward peak shaving modes—the control device prioritizes the compensation of fundamental positive-sequence current; in these two modes, losses are reduced by decreasing the transmission of active power. In contrast, in States ④ and ⑤, the control device prioritizes the compensation of fundamental positive-sequence reactive power and negative-sequence current; in these modes, losses are reduced by decreasing reactive power and unbalanced current.

TABLE III. COMPARISON OF EFFECT BEFORE AND AFTER COMPENSATION

State	Before		After	
	loss	current imbalance	loss	current imbalance
①	4.04kW	16.53%	2.16kW	23.47%
②	0.8kW	45.95%	0.34kW	211.64%
③	0.8kW	45.95%	0.52kW	71.57%
④	1.23kW	33.39%	0.86kW	0%
⑤	4.04kW	16.53%	3.71kW	0%
⑥	1.23kW	33.39%	1.23kW	33.39%
⑦	0.8kW	45.95%	0.8kW	45.92%

The initial SOC and loss reduction values for each state are shown in Figure 9. In states ①, ②, ③, and ④, the loss reduction values are relatively high, whereas in state ⑤, the loss reduction value is relatively low. This is because the losses in states ①, ②, and ③ are primarily caused by fundamental forward-sequence current, and bidirectional clipping can achieve better loss mitigation results; compared to state ④, the proportion of fundamental forward-sequence current in the losses is higher in State ⑤, so the loss reduction value after power quality control is slightly lower than in State ④.

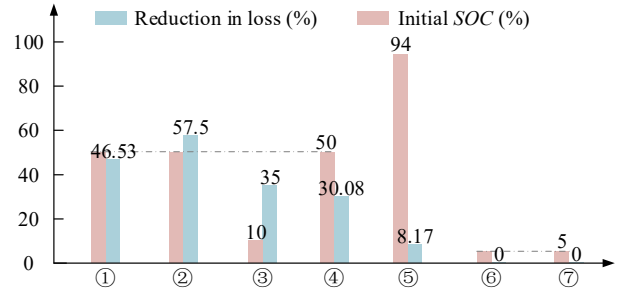


Figure 9. Initial SOC and reduction in loss for each state

In states ①, ②, and ③, the energy storage-based power control device prioritizes compensation for the fundamental positive-sequence current, resulting in an increased current imbalance. In these three states, the primary focus is on reducing power transmission to minimize losses.

V. CONCLUSION

This paper proposes an energy storage-based power control method designed to improve power quality and reduce losses in PV distribution substations. The research findings demonstrate that the proposed method can adaptively identify the operational status of distribution substations with PV and effectively regulate active and reactive power, as well as compensate for three-phase imbalance, under various operating conditions, thereby addressing the issues of deteriorating power quality and increased losses caused by the large-scale grid integration of distributed photovoltaic systems.

ACKNOWLEDGMENT

This work was supported in part by the science and technology project of China Southern Power Grid (031900KC24040023) and in part by the Science and

Technology Innovation Program of Hunan Province, China, under Grant (2023RC1038).

REFERENCES

- [1] H. H. H. Mousa, K. Mahmoud, M. Lehtonen, "Maximizing Hosting Capacity of Single-Phase Rooftop PVs in Unbalanced Distribution Systems," 2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Dubrovnik, Croatia, 2024, pp. 1-5.
- [2] J. Then, A. P. Agalgaonkar, K. M. Muttaqi, "Coordinated charging of spatially distributed electric vehicles for mitigating voltage rise and voltage unbalance in modern distribution networks," IEEE transactions on industry applications, vol. 59, no. 4, pp. 5149-5157, July-Aug 2023.
- [3] C. Zhao, G. Li, L. Zhang, B. Zhang, W. Tang, "A Regulation Method Considering Coupled Voltage Violation and Unbalance in Three-Phase Four-Wire Hybrid AC/DC LVDNs With High Penetration PVs," IEEE Transactions on Sustainable Energy, vol. 15, no. 2, pp. 1001-1012, April 2024.
- [4] A. Joseph, K. Smedley, S. Mehraeen, "Secure Power Distribution Against Reactive Power Control Malfunction in DER Units," IEEE Transactions on Power Delivery, vol. 36, no. 3, pp. 1552-1561, June 2021.
- [5] G. C. Kryonidis, K. N. D. Malamaki, S. I. Gkavanoudis, "Distributed Reactive Power Control Scheme for the Voltage Regulation of Unbalanced LV Grids," IEEE Transactions on Sustainable Energy, vol. 12, no. 2, pp. 1301-1310, April 2021.
- [6] H. Gharavi, L. F. Ochoa, X. Liu, G. Paterson, B. Ingham and S. McLoone, "CVR and Loss Optimization Through Active Voltage Management: A Trade-off Analysis," IEEE Transactions on Power Delivery, vol. 36, no. 6, pp. 3466-3476, December 2021.
- [7] J. S. Döhler, R. Eriksson, J. G. Oliveira, "Voltage regulation during short-circuit faults in low voltage distributed generation systems," Electric Power Systems Research, vol. 234, pp. 110596, September 2024.
- [8] S. Lakshmi, S. Ganguly, "Coordinated Operational Optimization Approach for PV Inverters and BESSs to Minimize the Energy Loss of Distribution Networks," IEEE Systems Journal, vol. 16, no. 1, pp. 1228-1238, March 2022.
- [9] T. Gangwar, N. P. Padhy, P. Jena, "Energy Management Approach to Battery Energy Storage in Unbalanced Distribution Networks," IEEE Transactions on Industry Applications, vol. 60, no. 1, pp. 1345-1356, Jan-Feb 2024.
- [10] X. Wu, C. Yang, G. Han, "Energy loss reduction for distribution networks with energy storage systems via loss sensitive factor method," Energies, vol. 15, no. 15, pp. 5453, July 2022.
- [11] J. Radosavljević, A. Ktena, M. Gajić, "Dynamic optimal power dispatch in unbalanced distribution networks with single-phase solar PV units and BESS," Energies, vol. 16, no. 11, May 2023.
- [12] R. Zahedi, A. Ahmadian, K. SedghiSigarchi and R. Gadh, "An Optimal Methodology for Mitigating the Impacts of EVs and Solar Systems on the Grid by Utilizing Existing Residential Battery Storage Capacity With No Further Grid Upgrades," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, pp. 1-5, July 2023.