IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 26 May 2023, accepted 20 June 2023, date of publication 26 June 2023, date of current version 6 July 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3289396

RESEARCH ARTICLE

A Coordination Scheme for Operating a Residential Photovoltaic-Based Village Power Grid

YU FU[1], YANG WANG[1], YONGXIANG CAI[1], (Member, IEEE), ANJIANG LIU[1], YI WEN[1], HONGWEI LI[2], JIAKUAN REN[1], AND YANGQUAN QU[1]

[1]Power Science Research Institute, Guizhou Power Grid Company Ltd., Guiyang, Guizhou 550002, China
[2]Qingdao Topscomm Communication Company Ltd., Qingdao 266109, China

Corresponding author: Yongxiang Cai (hli6@gzu.edu.cn)

This work was supported in part by the China Southern Power Grid under Grant GZKJXM20220044.

ABSTRACT In order to form a collaborative operation between village power grid and the end users, a two-stage management strategy is proposed where residential photovoltaic power systems have been linked to the distribution network in a rural area. At stage one, a regulation method considering active and reactive power is formed with a purpose of maintaining power grid within a security domain in operation; at stage two, to maximize the benefits of both the grid and its costumers, a "grid-user" interactive strategy is established so as to allow both the grid and users have opportunities and privileges equally. At the second stage, the power grid takes economics as an objective while delivering the extra benefits to the user as an incentive reward to improve the costumers income while avoiding extra resource investment to reach the same purpose. The test results show that the proposed strategy can effectively ensure the security of the network while improving the economy of the network operator and users.

INDEX TERMS Coordination operation, low-voltage distribution network, residential photovoltaic power systems, two-stage energy management scheme.

I. INTRODUCTION

The past decades have witnessed the severe energy crisis and climate issues, which lead countries across the world to be active in promoting the uses of renewable energy and their energy efficiency [1]. China shows a "high proportion, decentralized" photovoltaic development trend in recently years. According to a statistics in 2021, China has produced photovoltaic about 29 million kilowatts, accounting for about 55% of the total PV generation capacity globally [2]. This growing PV generation lead the promotion of PV power generation being integrated into low-voltage distribution networks (LVDN) in China in recent years which is getting popular in villages or rural areas since the nation encouragement with economic benefits. However, weak grid structure and infrastructure incur village grid more vulnerable, which brings about the key issues such as insufficient regulation capacity of voltage, severe network loss and large difference between peak and valley [3]. A large number of grid-connected equipment (energy storage, voltage regulator, distribution switch, etc.) are requested to ensure the security in network operation in order to cope with distributed PV power system from the users. That brings huge investment and increase operation and maintenance costs [4]. Moreover, lack of an interactive relationship between power grid operators and users, a large number of flexible resources on the user side cannot participate in the regulation of the power grid, leading to a great waste of resources [5]. Therefore, how to reduce the above adverse effects, a cooperative scheme is developed in this paper.

Distribution energy management system(DEMS) is to optimize the management of controllable equipment in the distribution network through control and communication technology, so as to improve the operation quality of networks. Literature [6] studies a DEMS for the optimal management of renewable energy sources, energy storage

The associate editor coordinating the review of this manuscript and approving it for publication was Inam Nutkani.

device and a variable-speed diesel generator. Literature [7] aims to improve the system stability and reduce the operation cost. The study proposed switch layout method by using a distribution network segment in the case of distributed power grid connection. Literature [8] has studied a distribution network by re-configuring a distributed generation distribution model with the goal of minimizing network line loss with a purpose of improving power quality. However, there still remains unsolved problems in low-voltage distribution networks since high permeability distributed PV generally brings about insufficient regulation capacity.

Home energy management system (HEMS) is to optimize the management of controllable loads from the user side by various algorithms or schemes, so as to improve the power economy for their costumers. Aim at reducing electricity cost, literature [9] has proposed an algorithm to optimize the operation of household appliances by using electricity price information. Literature [10] aims to reduce the electricity cost, and studied the optimization of the operation of household appliances for rooftop photovoltaic users through a Grey-Wolf algorithm. However, it is difficult to fully coordinate the electrical equipment with other appliances. It has been seen that HEMS with energy storage equipment have attracted a lots interests in recent years. Literature [11] studied a user optimization model containing photovoltaic, fuel cell and batteries with the goal of reducing electricity cost. However, a large amount of resources contained in the user side are still not used by the power grid, resulting in a great waste of resources.

The goals of DEMS and HEMS are contradictory. Considering DEMS only may increase the investment of power grid while reducing the income of users. In the case of considering HEMS only cannot solve the security problems when massive photovoltaic power units being connected with grid [12]. To coordinate the DEMS and HEMS, demand-side response approaches have been used [13], which encourage industrial and commercial stakeholders to carry out load transferring to make a good effect of peak shifting and valley filling. However, the situation become more challenging when the explosive growth of ultra-low load distributed rural areas. Moreover, the unified electricity price information are unable to guide the orderly grid connection of rooftop photovoltaic in the most of cases. Based on a game-theoretic approach [14], an electricity price function is defined according to the consumption characteristics of a generator set. However, it is weak when a large number of distributed photovoltaic power sources are involved. In addition, the randomness, autonomy and privacy of the user are not fully considered.

This paper proposes a two-stage energy management strategy to improve the interactions between a LVDN and users. At stage one, a secure operational range is considered where both the power grid and users can define their own adjustable power as constraint condition in the model to ensure the security of the network operation. At stage II, with privacy protection, a coordination strategy between DEMS and HEMS are proposed under the operation of a three-phase four-wire network model, the purpose of the scheme on this stage is to improve the operational quality and users economy with an additional benefit of no extra investment needed for regulation equipment for the power grid.

II. SYSTEM MODEL

A. THE PRINCIPLE OF SECURITY DOMAIN DEFINITION

At the first stage, security operation is the priority. Since the PV units are linked directly to the different lines over LVDN. Moreover, PV power generated are not constant over 24 hours a day. There exists the great challenges of imbalance across the lines. Furthermore, the electricity consumed by the customers on the LVDN is changeable with great uncertainty in practice. Those factors brings about the security issues which may lead to the grid collapse. In stage one, the security issues are concerned where node voltage and line current over LVDN are selected as the security constraint. They are implemented as the constraints in Stage one optimization as formula 3 shown. Therefore, the power grid provide all resources (including grid-side energy storage systems, static var generator, etc.) to ensure the safe and stable operation of the network. When the security operation cannot be ensured, for instance, extremely large amount of PV power injects into the grid, the grid security remaining problems while all adjustable resources from the grid exhausted. In this case, the customers have the responsibility to participate in the adjustment of the network to prevent grid collapse. At this stage, the overall adjustable active power and reactive power are deployed to the user side.

At stage two, the responsibility amount are defined for all users according to the PV capacity or size. The greater the photovoltaic capacity are, the greater responsibility the user are. Therefore, on the 2nd stage, security domain model are used to define regulation boundary of the user power. The same size of PV capacity of the users have a same security domain. This is due to an assumption that a larger capacity of PV unit may inject more power to the grid. Thus, they have more responsibility to regulate active or inactive power to the grid. Meanwhile, a larger PV unit of a user start to regulate prior to a smaller counterpart.

B. TWO-STAGE ENERGY MANAGEMENT

A two-stage energy management architecture are shown in Figure 1.

At the first stage, the network operation security is a priority while taking into account the fairness between users. First of all, grid parameters, such as photovoltaic access points, load demand, active and reactive power, regulation capacity of each node are collected. Then, adjustment amount of each node is defined by the steady-state security domain. Finally, the energy storage system (ESS) and the static reactive power generator (static var generator, SVG) on the grid side are preferentially adjusted. When the adjustment capacity is insufficient, the adjustment is taken by the user's ESS and adjustable load.

At the second stage, under the constraints of the security domain, grid operation and user power economy are considered. Firstly, the grid sends the optimized adjustment requests and reward price information to the users. Then, the users participate the power regulation with inactive/active power from the ESS and from flexible adjustable loads.

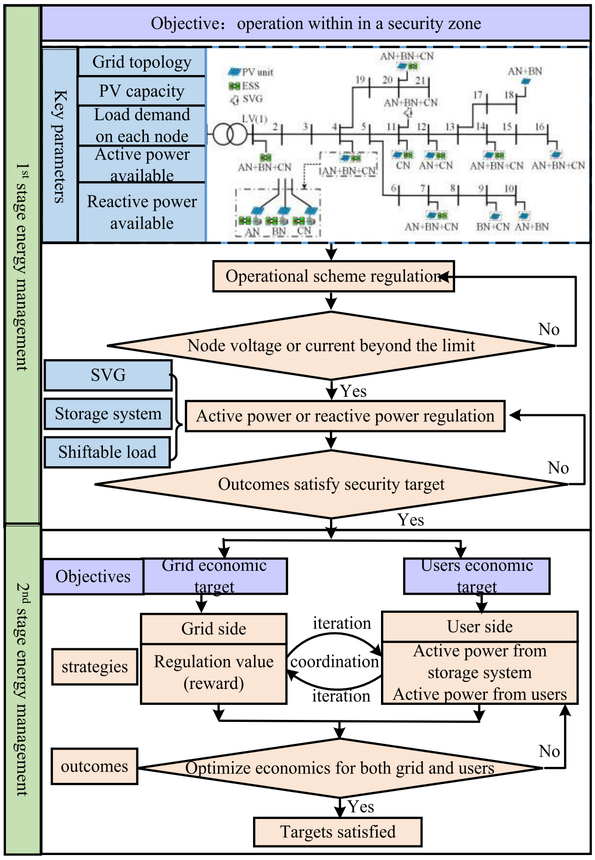


FIGURE 1. An architecture of a two-stage energy management scheme.

C. ENERGY TRANSMISSION AND INFORMATION INTERACTION

Figure 2 shows the energy and information flow over the two-stage regulation proposed. Firstly, this paper considers three types of low-voltage users, which are defined as follows: 1) configuration I: PQ nodes containing only user load that can only absorb active and reactive power; 2) configuration II: PQ nodes including rooftop PV users that can absorb/inject active and reactive power from/ to the grid; 3) configuration III: PQ nodes containing PV and ESS users that can both absorb and inject active and reactive power.

Secondly, information interaction are considered. Distribution intelligent gateway (DIG) establishes two-way communication between DEMS and each user. At the first step, each user communicates with DIG via line ň, and DIG communicates to HEMS via line . In addition, DIG communicates with DEMS over lines ő and ŕ. Among them, the system information is transmitted from DEMS to DIG, such as voltage level, network loss. The information transmitted from DIG to HEMS includes the target adjustment amount and reward price for each user while no direct control signals are generated for each HEMS. Afterwards, an HEMS receives local system information and define the adjustment strategies for the users. This method allows all users to have independent control and more choices while maintaining security of the private data from both the grid and households.

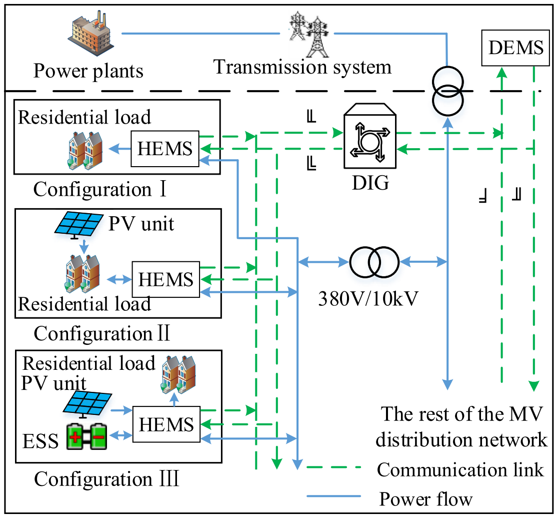


FIGURE 2. Mode of energy transmission and information interaction.

III. A TWO-STAGE MODEL

A. STAGE ONE MODEL

Steady state-state security region (SSR) can determine the range of power injection and absorption of the network with a purpose of safe and stable operation. At the same time, opportunity constraint planning is often used to solve the uncertainty of distributed photovoltaic power generation and load demand [15]. Therefore, this paper establishes an opportunity-constrained planning model based on the steady-state security domain to set the regulation amount of each node. Take "phase a" for example, the network has n + 1 nodes and nb lines. Ω_{V}, Ω_{I} refer to the safety domains of the node voltage and line current in the power injection space where $\Omega_V \in \mathbf{R}^{2n} \Omega_I \in \mathbf{R}^{2n}$.

$$\Omega_V := \{\boldsymbol{x}_\beta | \boldsymbol{V} \in \Re_V, f_{(V_0,\theta_0)}(\boldsymbol{V}, \theta) = \boldsymbol{x}_\beta\} \tag{1}$$

$$\Omega_I := \{\boldsymbol{x}_\beta | \boldsymbol{I}_l \in \Re_I, f_{(V_0,\theta_0)}(\boldsymbol{V}, \theta) = \boldsymbol{x}_\beta\} \tag{2}$$

$\boldsymbol{x}_\beta := (\boldsymbol{P}^{\mathrm{T}}, \boldsymbol{Q}^{\mathrm{T}})^{\mathrm{T}} \in \boldsymbol{R}^{2n}$ is the complex power vector injected into the node. R is the real set; $\boldsymbol{P} = (P_1, P_2, \ldots, P_n)^{\mathrm{T}}$ and $\boldsymbol{Q} = (Q_1, Q_2, \ldots, Q_n)^{\mathrm{T}}$ are the vectors of active and reactive power injected into the node; V is the node voltage amplitude vector; θ is the node voltage angle vector; I_l is the line current amplitude vector; $f_{(V_0,\theta_0)}(V, \theta) = x_\beta$ is the power flow function under the given voltage V_0 and current θ_0; and R_V and R_I are the constraints of the node voltage amplitude and the line current amplitude, respectively. They are the main factors reflecting security issues.

$$\begin{cases} \Re_V := \{\boldsymbol{V} \in \mathbf{R}^n | V_i^{\mathrm{m}} \le V_i \le V_i^{\mathrm{M}}, \forall i \in N\} \\ \Re_I := \{\boldsymbol{I}_l \in \mathbf{R}^{nb} | -I_{l,i}^{\mathrm{M}} \le I_{l,i} \le I_{l,i}^{\mathrm{M}}, \forall i \in B\} \end{cases} \quad (3)$$

where V_0, θ_0, are the voltage amplitude and the angle of the end node, V_i^M,, and V_i^m are the upper and lower limits of the node voltage amplitude respectively; $I_{l,i}^M$ is the upper limit of the line current amplitude; N is the set of nodes of the network; B is the set of lines of the network. $G \subset NL \subset N$ refer to the node sets with the devices, which can support active and reactive power regulation. The capacity constraints of the active and reactive power are defined as follows:

$$\begin{cases} \Re_P := \{\boldsymbol{x}_\beta | P_i^{\mathrm{m}} \le P_i \le P_i^{\mathrm{M}}, \forall i \in G\} \\ \Re_Q := \{\boldsymbol{x}_\beta | Q_i^{\mathrm{m}} \le Q_i \le Q_i^{\mathrm{M}}, \forall i \in L\} \end{cases} \quad (4)$$

whereP_i^{M} andP_i^{m} are the upper and lower limits of the node active power, respectively; Q_i^{M} and Q_i^{m} are the upper and lower limits of node reactive power, respectively. Therefore, considering constraints, such as node voltage, line current, and generation capacity, SSR in complex power injection space is defined as follows:

$$\Omega_{SS} := \Omega_V \cap \Omega_I \cap \Re_P \cap \Re_Q \quad (5)$$

where $\Omega_{SS} \in \mathbf{R}^{2n}$ is a convex polyhedron surrounded by a 2n-dimensional hyperplane. At the same time, the three-phase load imbalance rate in SSR was used to describe the degree of the three-phase imbalance in SSR while the three-phase imbalance constraint is consistent with [16], which is specifically calculated in reference [15]. During the regulation, the active and reactive powers injected and absorbed by the nodes are as follows:

$$\begin{cases} P_i = \widetilde{P}_i + \Delta P_i, \forall i \in N \\ Q_i = \widetilde{Q}_i + \Delta Q_i, \forall i \in N \end{cases} \quad (6)$$

where: $\widetilde{P}_i$ and $\widetilde{Q}_i$ are the predicted values of the active and reactive power injection to the node i, respectively. ΔP_i and ΔQ_i are the variation of the active and reactive power injection of the node i, respectively.

B. STAGE TWO MODEL

1) OPTIMIZATION MODEL OF THE POWER DISTRIBUTION NETWORK

a: OPTIMIZE GOALS

With the goal of minimizing network loss, the optimal power flow model of the three-phase four-wire distribution network is established. The optimized variables are active power and reactive power of energy storage device on the grid side, and the adjustable reactive power and active power of SVG on the user side [17]:

$$\min F = \sum_{t=1}^{T} P_t^{\mathrm{loss}} \Delta t \quad (7)$$

$$P_t^{\mathrm{loss}} = [\boldsymbol{I}_t^{\mathrm{line}*} \otimes \boldsymbol{I}_t^{\mathrm{line\,T}}]\boldsymbol{R}^{\mathrm{line}} \quad (8)$$

$$\boldsymbol{I}_t^{\mathrm{line}} = \boldsymbol{M}\boldsymbol{V}_t \quad (9)$$

$$\boldsymbol{V}_t = \boldsymbol{Y}^{-1}\boldsymbol{I}_t^{\mathrm{inj}} \quad (10)$$

where: P_t^{loss} represents the network loss at time t; $\boldsymbol{I}_t^{\mathrm{line}}$ is a compound matrix including the branch current amplitude and phase angle; $\boldsymbol{R}^{\mathrm{line}}$ is the branch resistance matrix; $*$ is the conjugate; $\otimes$ stand for the multiplication of the corresponding elements of two matrix; M is the correlation matrix of node and branch;$\boldsymbol{V}_t$ is the matrix of the voltage of each node; $\boldsymbol{Y}^{-1}$ is the inverse matrix of the node conduction matrix; $\boldsymbol{I}_t^{\mathrm{inj}}$ is composed of the injected current of each node. The elements in the matrix are as follows:

$$I_{i,\varphi,t} = \frac{1}{U_{i,\varphi,t}^*}[P_{i,\varphi,t} - \mathrm{j}Q_{i,\varphi,t}] \quad (11)$$

$$P_{i,\varphi,t} = P_{i,\varphi,t}^{\mathrm{PV}} + P_{i,\varphi,t}^{\mathrm{G,\,ESS}} + P_{i,\varphi,t}^{\mathrm{LOAD\text{-}m}} \quad (12)$$

$$Q_{i,\varphi,t} = Q_{i,\varphi,t}^{\mathrm{G,\,ESS}} + Q_{i,\varphi,t}^{\mathrm{SVG}} - Q_{i,\varphi,t}^{\mathrm{LOAD\text{-}m}} \quad (13)$$

where $I_{i,\varphi,t}$ is the injected current to the node; $U_{i,\varphi,t}$ refers to the nominal voltage of the node; $P_{i,\varphi,t}^{\mathrm{PV}}$ refers to the active power. $P_{i,\varphi,t}^{\mathrm{G,\,ESS}}$ and $Q_{i,\varphi,t}^{\mathrm{G,\,ESS}}$ refer to the active power and reactive power from the energy storage device on the grid side, respectively. $P_{i,\varphi,t}^{\mathrm{LOAD\text{-}m}}$ and $Q_{i,\varphi,t}^{\mathrm{LOAD\text{-}m}}$ refer to the active and reactive power of the node load, respectively. $Q_{i,\varphi,t}^{\mathrm{SVG}}$ refers to the SVG reactive power; i is the node number; φ represents the phase (a, b or c); and t is time step.

Constraints: voltage, current, power and three-phase imbalance.

The node voltage and branch current constraints meet formula (3); the net power constraint of each node meets formula (5); the three-phase imbalance constraint, neutral line voltage constraint, energy storage model and constraint are consistent with the calculation in [17]. In addition, the adjustable range of the user power must be limited as follows,

$$P_{i,\varphi,t}^{\mathrm{LOADmin}} \le P_{i,\varphi,t}^{\mathrm{LOAD\text{-}m}} \le P_{i,\varphi,t}^{\mathrm{LOADmax}} \quad (14)$$

where $P_{i,\varphi,t}^{\mathrm{LOADmin}}$ and $P_{i,\varphi,t}^{\mathrm{LOADmax}}$ are the upper and lower limits of user active power regulation respectively.

b: INCREMENTAL BENEFIT CONSTRAINTS

The network loss saved by user participation in regulation is regarded as the incremental benefit given by network operation as follows:

$$I_{\mathrm{net}} = (Q_{\mathrm{c}} + \mu_{\mathrm{c}} K_{\mathrm{c}})\Delta W^{\mathrm{loss}} \quad (15)$$

$$\Delta W^{\mathrm{loss}} = \sum_{t=1}^{T}[P_{\mathrm{before},t}^{\mathrm{loss,}} - P_{\mathrm{after},t}^{\mathrm{loss}}]\Delta t \quad (16)$$

where I_{net} refers to the incremental benefit from network operation; Q_{c} refers to the cost of power generation per KWH;

μ_c refers to the cost of carbon tax; K_c refers to the CO_2 amount generated by traditional coal-fired power plants per KWH; ΔW^{loss} refers to the variation of the network loss; $P^{\text{loss,}}_{\text{before},t}$ and $P^{\text{loss}}_{\text{after},t}$ refer to the network loss before and after the user adjustment, respectively. They can be calculated according to Equation (8).

2) THE USER-BASED OPTIMIZATION MODEL

a: OPTIMIZE GOALS

The optimization formula for the user side is established from the perspective of the optimal economic cost. The objective function of the user revenue at node i is as follows [19]:

$$\max f_i = \sum_{\varphi\in\Phi} C^{\text{G}}_{i,\varphi} + \sum_{\varphi\in\Phi} C^{\text{DR}}_{i,\varphi} - \sum_{\varphi\in\Phi} C^{\text{ESS}}_{i,\varphi} \tag{17}$$

where Φ is a three-phase set; $C^{\text{DR}}_{i,\varphi}$ refers to the income of the users due to adjustment response; $C^{\text{ESS}}_{i,\varphi}$ refers to the cost due to the ESS charge and discharge on the user side; $C^{\text{G}}_{i,\varphi}$ refers to the purchase cost or sale incomes of electricity from the user side as follows,

$$C^{\text{G}}_{i,\varphi} = \begin{cases} \gamma_t^{\text{buy}} \sum_{t=1}^{T} P^{\text{G}}_{i,\varphi,t}\Delta t, & P^{\text{G}}_{i,\varphi,t} < 0 \\ \gamma_t^{\text{sell}} \sum_{t=1}^{T} P^{\text{G}}_{i,\varphi,t}\Delta t, & P^{\text{G}}_{i,\varphi,t} > 0 \end{cases} \tag{18}$$

where $P^{\text{G}}_{i,\varphi,t}$ refers users purchase or selling power from/to the utility company; γ_t^{buy} refers to power purchase price; γ_t^{sell} refers to power sale price; Δt refers to time interval; T is the total duration.

$$C^{\text{DR}}_{i,\varphi} = \varepsilon_{i,\varphi,t} \sum_{t=1}^{T} P^{\text{DR}}_{i,\varphi,t}\Delta t \tag{19}$$

where $\varepsilon_{i,\varphi,t}$ refers to an additional reward of the users due to their response to the grid; $P^{\text{DR}}_{i,\varphi,t}$ refers to the power from adjustment response by the users.

$$C^{\text{ESS}}_{i,\varphi} = \eta_s \sum_{t=1}^{T} (P^{\text{char}}_{i,\varphi,t} + P^{\text{disc}}_{i,\varphi,t})\Delta t \tag{20}$$

$$\eta_s = \frac{C^{\text{P,ESS}}_s}{2E^{\text{ESS}}_s} \tag{21}$$

where $P^{\text{char}}_{i,\varphi,t}$ and $P^{\text{disc}}_{i,\varphi,t}$ refer to the charge and discharge power of ESS respectively; η_s charge and discharge cost of ESS (assuming the cost of charge and the cost of discharge are same); E^{ESS}_s refers to ESS capacity of type S. The operating cost of a full charge and discharge is calculated as follows,

$$C^{\text{P,ESS}}_s = \frac{C^{\text{capital}}_s}{N^{\text{ESS}}_s(x)} \tag{22}$$

where C^{capital}_s is the investment cost for EES; $N^{\text{ESS}}_s(x)$ refers to the total charge-and-discharge cycles of EES, determined by the charge-discharge depth x, which is specifically calculated by [20].

Constraints:

Power balance constraint.

$$P^{\text{G}}_{i,\varphi,t} = P^{\text{LOAD}}_{i,\varphi,t} - P^{\text{TR}}_{i,\varphi,t} - P^{\text{PV}}_{i,\varphi,t} - P^{\text{ESS}}_{i,\varphi,t} \tag{23}$$

$P^{\text{LOAD}}_{i,\varphi,t} P^{\text{TR}}_{i,\varphi,t} P^{\text{ESS}}_{i,\varphi,t}$ where: for user load; for user adjustable load; charge or discharge power for EES.

Energy storage system constraints

SOC refers to the state of charge of the EES, which can be calculated as follows,

$$S^{\text{SOC}}_{i,\varphi,t+\Delta t} = S^{\text{SOC}}_{i,\varphi,t} + \frac{P^{\text{char}}_{i,\varphi,t}\eta^{\text{char}}_s\Delta t}{E^{\text{ESS}}_s} - \frac{P^{\text{disc}}_{i,\varphi t}\Delta t}{\eta^{\text{disc}}_s E^{\text{ESS}}_s} \tag{24}$$

where $S^{\text{SOC}}_{i,\varphi,t}$ and$S^{\text{SOC}}_{i,\varphi,t+\Delta t}$ refer to the SOC at t and $t+\Delta t$, respectively; η^{char}_s and η^{disc}_s refer to the charging and discharge efficiency, respectively.

$$S^{\text{SOC}}_{\min} \le S^{\text{SOC}}_{i,\varphi,t} \le S^{\text{SOC}}_{\max} \tag{25}$$

$$\begin{cases} 0 \le P^{\text{char}}_{i,\varphi,t} \le P^{\text{charmax}}_{i,\varphi,t} \\ 0 \le P^{\text{disc}}_{i,\varphi,t} \le P^{\text{discmax}}_{i,\varphi,t} \end{cases} \tag{26}$$

where $S^{\text{SOC}}_{\max}$ and$S^{\text{SOC}}_{\min}$ are the upper and lower limits of the SOC, respectively; $P^{\text{charmax}}_{i,\varphi,t}$ and $P^{\text{discmax}}_{i,\varphi,t}$ are the maximum charge and discharge power, respectively.

Power constraint of the adjustable load

$$0 \le P^{\text{TR}}_{i,\varphi,t} \le P^{\text{TR.max}}_{i,\varphi,t} \tag{27}$$

where $P^{TR.max}_{i,\varphi,t}$ is the upper limit of the user-adjustable load.

C. A TWO-STAGE REGULATION SCHEME

A flow chart of the two-stage adjustment scheme is shown in Figure 3. The operation can be divided into three parts: initialization, stage one and stage two. The second-stage optimization is relaxed by a second-order cone programming method. Second order cone relaxation(SOCR)is a popular method for calculating the optimal power flow in distributed power network where the optimization function may include non-convex constraints. The searching process may lead to a local optimum option due to those non-convex constraints [17]. By employing SOCR package in MATLAB 2018b, this study transmits optimization objectives and the restraints into second order cone programming(SOCP) to make sure the solution is the global optimal candidate over optimization searching. The programming is completed by on environment MATLAB 2018b with the YALMIP platform. CPLEX algorithm package is called to solve the optimization. The programme follows the way as below,

1) PROGRAM INITIALIZATION

Firstly, we collect the parameters, including network topology, line parameters, PV power, load, and active power/reactive power regulation capacity of each node. Then, according to equation (1) - (5), a model based on steady-state security domain and chance constraints is established. The range of steady-state security domain is calculated.

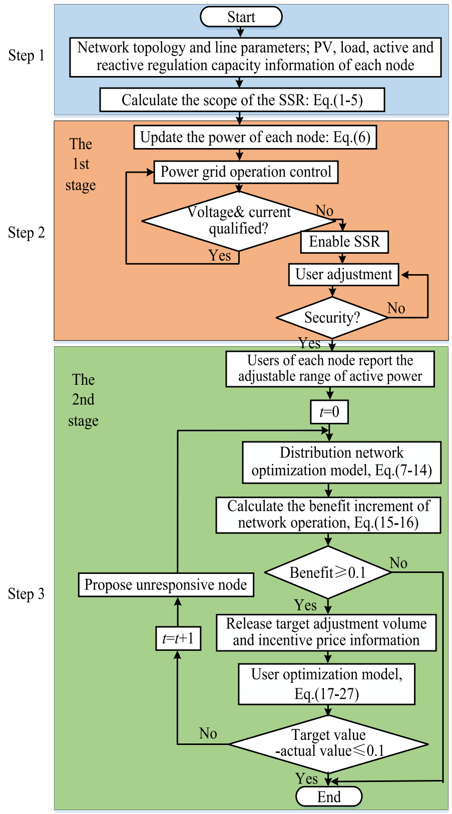


FIGURE 3. Flow chart of two-stage operation.

2) PHASE I PROCESS

The changes of the active and reactive power over each node are updated according to formula 6. The power grid runs the operational scheme. If the voltage or branch current of each node is out of the security domains, the adjustment amount of each node over the grid is calculated through the steady-state security constraints. The changes are implemented by regulating energy storage device and adjustable load.

3) PHASE II PROCESS

First of all, each user node reports the adjustable range of active power. Secondly, DEMS calculates the target amount according to the optimization by Equations (7) - (14). The increment rewards by network operation are also calculated according to Equations (15) and (16). Information on both target amount and the rewards are sent to all the user nodes. Thirdly, the users who respond to the adjustment scheme determine the most economical strategy according to the user optimization model in formulas (17) - (27). Next, DEMS performs the next round optimization while the non-respond users are eliminated in this case. Therefore, decision space over iterative optimization process shrinks due to the reduction of users involved in optimization until a convergent solution are received [21]. DEMS updates the target adjustment and the reward information while the users respond again. The iteration completes as the increment of the operating benefit from the network is less than 10^{-1}. Alternatively, The iteration ends as the discrepancy between the target adjustment and the actual counterparts is less than 10^{-1}.

IV. CASE STUDIES

A. GENERAL INFORMATION OF THE CASES

The grid topology is formed by 21-node three-phase four-wire network as shown in Figure 4. The rated voltage is 380V with the distance of each line 50m. The line impedance parameters per unit length are shown in Table 1. The reference load is shown in Table 2. Table 3 has listed the deployment of PV and ESS. The price information is demonstrated in Table 4. The remaining parameters are included in Table 5. Tables 1-5 are listed in Appendix A.

Figure 5 shows the 24h power curve of the grid-connected photovoltaic and load while the power is the unitary value. The majority power generation by PV is over the period from 8:00 to 17:00. During this period, a large amount of surplus power of photovoltaic is injected into the low-voltage distribution network through each node, resulting in voltage surge. The high load period is 17:00-19:00. At this time, the photo-voltaic power generation power is insufficient to support the user's load, resulting in the voltage exceeding the lower limit.

B. STRATEGIES IN SIMULATION

In order to analyze the effect of the proposed strategy, the simulation includes four strategies:

1) EMS-0: No optimized management strategy is used as the benchmark results for comparison with other strategies.

2) EMS-1: Using the centralized optimization control idea of the traditional low-voltage distribution network in literature [17]. The optimal power flow model is established with the goal of minimum network loss. Without considering the user-side resources. It only adjusts the EES and SVG on the grid side.

3) EMS-2: the two-stage adjustment strategy proposed in this paper. The first stage adopts responsibility adjustment. The second stage adopts interactive adjustment mode. The overall architecture is shown in Figure 4.

4) EMS-3: It still adopts the centralized control idea mentioned in literature [17]. The power grid increases the equipment investment to achieve the same regulatory resources as EMS-2.

C. REGULATION RESULTS OF THE GRID SIDE

The voltage deviation in the network can be measured by the maximum voltage deviation index (MVDI), defined as follows:

$$V_{\mathrm{dev}} = \max \frac{|V_i - V_{\mathrm{ref}}|}{V_{\mathrm{ref}}} \times 100\% \quad \forall i \in N \tag{28}$$

where V_{ref} is the reference voltage of the node. As the user's adjustable resources involve the EES and the adjustable load. The adjusted amount of each node is converted into the investment cost of the EES under strategy EMS-3. The energy

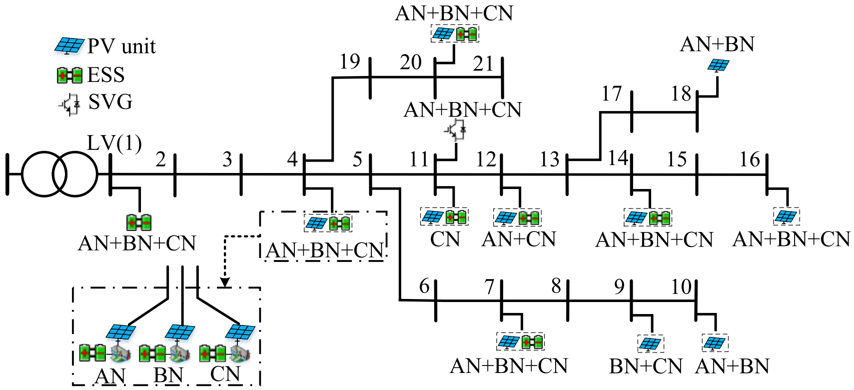


FIGURE 4. The architecture of the studied grid.

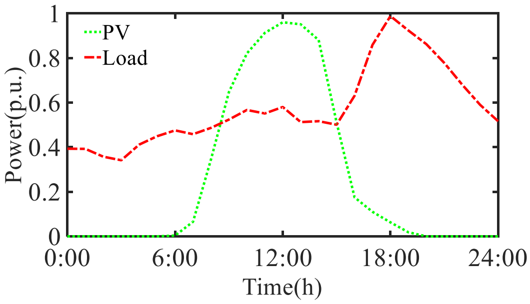


FIGURE 5. The 24h-power curves of photovoltaic and the load.

storage equipment is battery. The cost can be calculated as follows,

$$C_{\text{sum}} = (C_{\text{unit}}^{\text{cap}} + C_{\text{unit}}^{\text{OM}} + C_{\text{unit}}^{\text{rep, ess}}) \sum_{i=1}^{N} \sum_{t=1}^{T} P_{i,\varphi,t}^{\text{r}} \Delta t \quad (29)$$

where C_{sum}, $C_{\text{unit}}^{\text{cap}}$, $C_{\text{unit}}^{\text{OM}}$, $C_{\text{unit}}^{\text{rep, ess}}$ refer to the total investment cost of the power grid, the energy storage investment costs per unit capacity, the operation and maintenance costs per unit capacity of the EES, the energy storage replacement cost per unit capacity [22]. $P_{i,\varphi,t}^{\text{r}}$ refers to the active power as the users response the adjustment. For the No.16 node, as the voltage amplitude changes, the simulation results are shown in Figure 6. The voltage amplitude is the unitary value. Since node 16 locates at the end, which is most likely to have over / under-voltage problems. Table 4 shows the simulation results in line with MVDI, network loss and total equipment investment under different strategies.

As can be seen from both Table 4 and Figure 6: 1) The MVDI under the EMS-1 strategy is 8.84% with the network loss of 80.13 kW · h. The results indicate that the traditional regulation mode completely relies on the power grid. It tends to have the problem of voltage over/under shoot and large network loss due to insufficient regulation capacity; 2) Compared with EMS-1, MVID in EMS-2 and EMS-3 decreases by 2.94% and 3.76% respectively as. Voltage overshoots are effectively solved. Moreover, network loss is reduced by 60.41% and 66.34% respectively in cases EMS-2 and EMS-3, which mean the network loss is also greatly improved. This indicates that the operation control effectiveness are greatly improved by increasing the regulating equipment and rationally utilizing the adjustment potential of users; 3) EMS-2 and EMS-3 have similar effects. However, EMS-3 has increased the investment by $7.47*10^5$ Chinese yuan compared with the counterpart of EMS-2. This indicates that EMS-2 has improved the system economy by avoiding extra cost for adding grid equipment while maintaining the same regulation effects with EMS-3.

D. REGULATION RESULTS OF THE USER-SIDE

In order to reasonably encourage the users to participate in the adjustment, the incremental benefits from the grid in the second stage are given as an additional reward to the users. The reward price $\varepsilon_{i,\varphi,t}$ is calculated by the equivalent benefit due to grid loss reduction dividing the amount of adjustable power from the user. Formula 30 gives the calculation details.

$$\epsilon_{i,\varphi,t} = \frac{I_{net}}{\sum_{t=1}^{T} \Delta P_{i,\varphi,t}^{ref} \cdot \Delta t} \quad (30)$$

where I_{net} refers to the incremental benefit from network operation; and $\Delta \text{P}_{\text{i},\varphi,\text{t}}^{\text{ref}}$ refers to the contributed power to the grid by user participation in the stage II regulation.

The users comprehensively consider the cost and benefit before deciding to response to the grid regulation or not. The adjustment strategy and reward price of each node are shown in Figure 7.

As can be seen in Figure 7, the rewards of the participating users, such as nodes 11,12 and 16, is relatively high, which is due to the good adjustment performance of these nodes so as to promote more incremental benefits to the power grid in the first place. Secondly, the reward price is positively correlated with the adjustment amount, indicating that the high reward can encourage the users to be involved and find significant potentials in regulation schemes. Thirdly, the high reward can also lead the user side to allocate their resources reasonably.

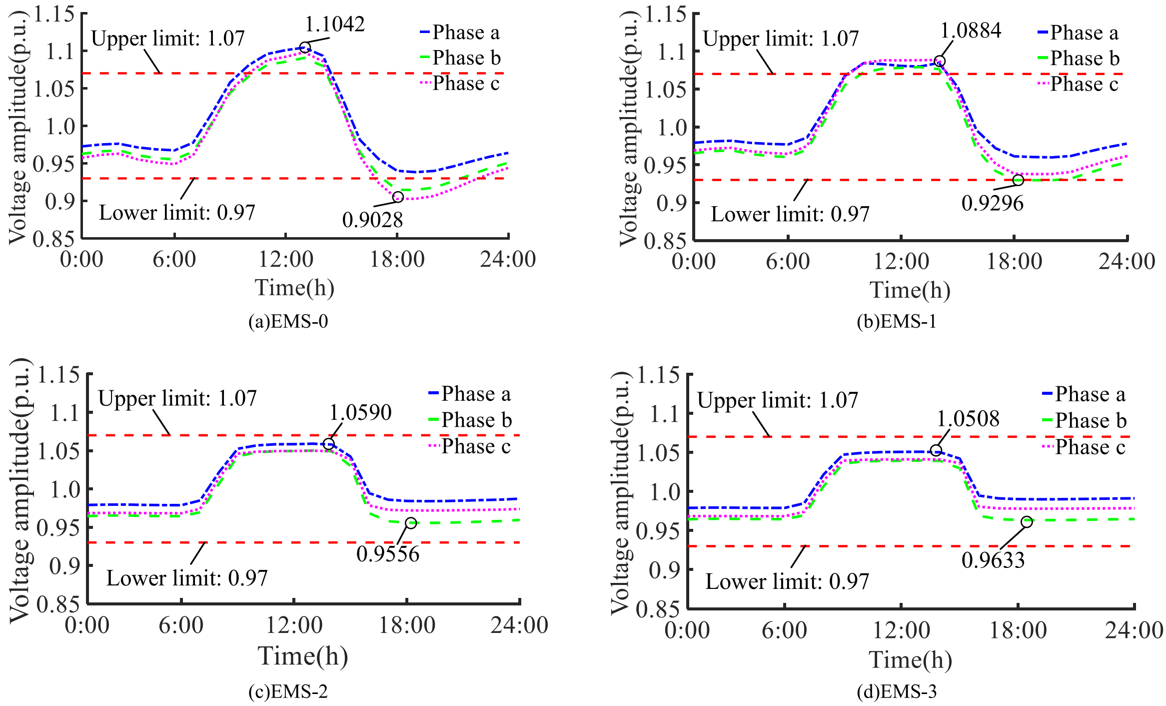


FIGURE 6. Voltage amplitude curves at No.16 node.

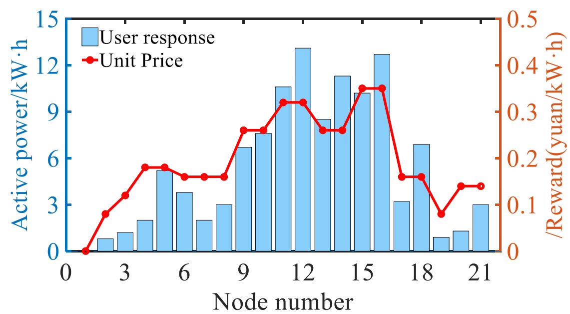


FIGURE 7. Adjustment strategy and reward price.

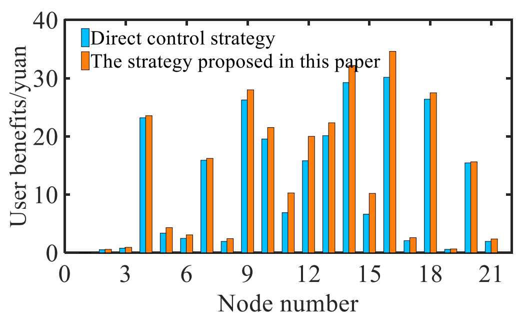


FIGURE 8. Comparison of user revenue.

In order to further analyze the proposed strategy in association to the user economy promotion, this study has compared with the conventional control method as the grid regulates the user resources by providing compensations with normal utility price to the users (no additional reward). The user revenue has shown in Figure 8.

As can be seen from Figure 8, the total user revenue has increased from 249.3 to 279.0 RMB, with an increase of 11.0%. Because the method of this paper considers that the user participation in the adjustment to get additional rewards while the users take the economy to optimize their adjustment strategies.

V. CONCLUSION

With the access of massive distributed PV power to the low-voltage distribution network, the serious security issues and stability of village grid encounter tremendous challenges. Moreover, optimal operation of the power grid while maintaining users' economy are also critical for the stakeholders in power industries. Therefore, a two-stage energy management strategy based on coordination and interaction between the power grid and users is proposed. The key findings of the study can be summarized as follows:

1) based on a principle of the security and fairness, a method considering power grid privilege and the responsibility of users is proposed at the first stage where a steady-state security domain and opportunity-based constraints are used. Considering the economy, an interactive strategy with privacy protection is established at the second stage, which attracts the both interests from the grid and users.

2) Compared with the traditional power grid, the voltage deviation under the proposed strategy is 5.90% (reduced by 2.94%), which effectively solves the security problem of the network with the benefit of no extra investment for the power grid.

TABLE 1. Impedance parameters of unit length line.

The first end	2_A(Ω/km)	2_B(Ω/km)	2_C(Ω/km)	2_N(Ω/km)
1_A	0.65000+j0.41200	0.00650+j0.00412	0.00650+j0.00412	0.00650+j0.00412
1_B	0.00650+j0.00412	0.65000+j0.41200	0.00650+j0.00412	0.00650+j0.00412
1_C	0.00650+j0.00412	0.00650+j0.00412	0.65000+j0.41200	0.00650+j0.00412
1_N	0.00650+j0.00412	0.00650+j0.00412	0.00650+j0.00412	0.65000+j0.41200

TABLE 2. Base load of 21-node LVDN.

Line number	The first node	The end node	Base value/Ω							
			P_a	Q_a	P_b	Q_b	P_c	Q_c	P_n	Q_n
1	0	1	2.0045	0.8018	0.9450	0.3780	1.6400	0.6560	0	0
2	1	2	1.7871	0.7148	2.3520	0.9408	1.4400	0.5760	0	0
3	2	3	1.5456	0.6182	1.3020	0.5208	1.7000	0.6800	0	0
4	3	4	1.3524	0.5410	1.7640	0.7056	2.3400	0.9360	0	0
5	4	5	0.0000	0.0000	0.0000	0.0000	4.6800	1.8720	0	0
6	5	6	3.2844	1.3138	4.0320	1.6128	2.9000	1.1600	0	0
7	6	7	0.0000	0.0000	2.5410	1.0164	2.9600	1.1840	0	0
8	7	8	0.0000	0.0000	2.5830	1.0332	3.1200	1.2480	0	0
9	8	9	2.9946	1.1978	1.4280	0.5712	1.7000	0.6800	0	0
10	4	10	2.1252	0.8501	2.1000	0.8400	2.4800	0.9920	0	0
11	10	11	0.0000	0.0000	2.3730	0.9492	3.0000	1.2000	0	0
12	11	12	2.0769	0.8308	1.4070	0.5628	1.9600	0.7840	0	0
13	12	13	1.8596	0.7438	0.7770	0.3108	3.3400	1.3360	0	0
14	13	14	0.0000	0.0000	2.1000	0.8400	1.7000	0.6800	0	0
15	14	15	3.4293	1.3717	2.2260	0.8904	0.0000	0.0000	0	0
16	12	16	1.2800	0.5120	2.0790	0.8316	1.5600	0.6240	0	0
17	16	17	0.0000	0.0000	1.1550	0.4620	0.9200	0.3680	0	0
18	3	18	0.0000	0.0000	3.6750	1.4700	3.1000	1.2400	0	0
19	18	19	1.8596	0.7438	3.0240	1.2096	3.9800	1.5920	0	0
20	19	20	3.2120	1.2848	2.0790	0.8316	2.8800	1.1520	0	0

TABLE 3. PV rated power and energy storage type of 21-node LVDN.

Phase	PV power at corresponding node (kW)										EES types at corresponding node					
	4	7	9	10	11	12	14	16	18	20	4	7	11	12	14	20
A	4	5	-	4	-	4	5	6	5	6	ESS1	ESS2	-	ESS1	ESS2	ESS2
B	4	5	6	4	-	-	5	6	5	6	ESS1	ESS2	ESS1	-	ESS2	ESS2
C	4	5	6	-	5	4	5	6	-	6	ESS1	ESS2	-	ESS1	ESS2	-

TABLE 4. Price tariff.

Time	Purchase price (RMB/kW·h)	Sale price (RMB/kW·h)
Peak hour (8:00-11:00, 18:00-23:00)	1.59	1.38
Average load hour (7:00-8:00, 11:00-18:00)	0.74	0.51
Valley hour (23:00-07:00)	0.53	0.32

3) Compared with conventional control method, the proposed strategy improves the user's revenue by 11.0%. The results may be a convinced evidence to encourage residential costumers with PV and EES units to allocate their resources reasonably. Moreover, the scheme in the study increases the grid resilience by considering the participation from both the grid resources and customers benefit while protecting users' privacy.

TABLE 5. Parameters in case studies.

Parameter attribute	Parameter name	Range
Model	voltage range at node	0.93~1.07p.u.
	reference voltage at node	1p.u.
	Line current range	-100A~100A
Grid-side ESS	Access node number	1
	Access phase	a、b、c
	Reference capacity	30kW·h
	Up limit of charging/discharging	5kW
Grid-side SVG	Access node number	11
	Access phase	a、b、c
	Reference power output, single phase	100kvar
User-side ESS1	Single phase capacity	16kW·h
	Up limit of charging/discharging	4kW
	Charging/discharging efficiency	92%
User-side ESS2	Single phase capacity	20kW·h
	Up limit of charging/discharging	5kW
	Charging/discharging efficiency	95%
SOC of EES	SOC range	10%~90%
Users	Node number of configuration one	1、2、3、5、6、8、13、15、17、19、21
	Node number of configuration two	9、10、16、18
	Node number of configuration three	4、7、11、12、14、20

The limitation of the study lies in the concerns on randomness, autonomy and privacy of the users being less discussed in this study which are recommended to be involved more in the future investigation.

APPENDIX

See Tables 1–5.

REFERENCES

[1] X. Chen, W. Cao, Q. Zhang, S. Hu, and J. Zhang, "Artificial intelligence-aided model predictive control for a grid-tied wind-hydrogen-fuel cell system," *IEEE Access*, vol. 8, pp. 92418–92430, 2020, doi: 10.1109/ACCESS.2020.2994577.

[2] National Energy Administration. *China's Grid Connected Installed Capacity of Photovoltaic Power Generation Has Exceeded 300 Million KW, and Distributed Development Has Become a New Bright Spot*. Jan. 2022. [Online]. Available: http://www.nea.gov.cn/2022-01/20/c_1310432517.htm

[3] F. Olivier, P. Aristidou, D. Ernst, and T. Van Cutsem, "Active management of low-voltage networks for mitigating overvoltages due to photovoltaic units," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 926–936, Mar. 2016, doi: 10.1109/TSG.2015.2410171.

[4] Y. Cai, W. Tang, O. Xu, and L. Zhang, "Review of voltage control research in LV distribution network with high proportion of residential PVs," (in Chinese), *Power Syst. Technol.*, vol. 42, no. 1, pp. 220–229, 2018.

[5] M. Zeraati, M. E. H. Golshan, and J. M. Guerrero, "Distributed control of battery energy storage systems for voltage regulation in distribution networks with high PV penetration," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3582–3593, Jul. 2018, doi: 10.1109/TSG.2016.2636217.

[6] M. S. Taha, H. H. Abdeltawab, and Y. A. I. Mohamed, "An online energy management system for a grid-connected hybrid energy source," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 4, pp. 2015–2030, Dec. 2018, doi: 10.1109/JESTPE.2018.2828803.

[7] B. Li, J. Wei, Y. Liang, and B. Chen, "Optimal placement of fault indicator and sectionalizing switch in distribution networks," *IEEE Access*, vol. 8, pp. 17619–17631, 2020, doi: 10.1109/ACCESS.2020.2968092.

[8] M. J. H. Moghaddam, A. Kalam, J. Shi, S. A. Nowdeh, F. H. Gandoman, and A. Ahmadi, "A new model for reconfiguration and distributed generation allocation in distribution network considering power quality indices and network losses," *IEEE Syst. J.*, vol. 14, no. 3, pp. 3530–3538, Sep. 2020, doi: 10.1109/JSYST.2019.2963036.

[9] B. Celik, R. Roche, D. Bouquain, and A. Miraoui, "Decentralized neighborhood energy management with coordinated smart home energy sharing," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6387–6397, Nov. 2018, doi: 10.1109/TSG.2017.2710358.

[10] L. Jing, Z. Xiangyu, L. Tao, L. Yue, and W. Qinghua, "Integrated optimization of smart home appliances under energy management system," in *Proc. IEEE 2nd Int. Conf. Digit. Twins Parallel Intell. (DTPI)*, Boston, MA, USA, Oct. 2022, pp. 1–6, doi: 10.1109/DTPI55838.2022.9998973.

[11] H. Ren, Q. Wu, W. Gao, and W. Zhou, "Optimal operation of a grid-connected hybrid PV/fuel cell/battery energy system for residential applications," *Energy*, vol. 113, pp. 702–712, Oct. 2016, doi: 10.1016/j.energy.2016.07.091.

[12] S. Hussain, C. Z. El-Bayeh, C. Lai, and U. Eicker, "Multi-level energy management systems toward a smarter grid: A review," *IEEE Access*, vol. 9, pp. 71994–72016, 2021, doi: 10.1109/ACCESS.2021.3078082.

[13] S. M. S. Siddiquee, B. Howard, K. Bruton, A. Brem, and D. T. J. O'Sullivan, "Progress in demand response and it's industrial applications," *Frontiers Energy Res.*, vol. 9, Jun. 2021, Art. no. 673176, doi: 10.3389/fenrg.2021.673176.

[14] J. He, Y. Li, H. Li, H. Tong, Z. Yuan, X. Yang, and W. Huang, "Application of game theory in integrated energy system systems: A review," *IEEE Access*, vol. 8, pp. 93380–93397, 2020, doi: 10.1109/ACCESS.2020.2994133.

[15] T. Yang and Y. Yu, "Steady-state security region-based voltage/var optimization considering power injection uncertainties in distribution grids," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2904–2911, May 2019, doi: 10.1109/TSG.2018.2814585.

[16] R. Ma and W. Ao, "Research on random fuzzy safety distance of active distribution network considering three-phase unbalance," (in Chinese), *Proc. CSEE*, vol. 40, no. 23, pp. 7600–7609, Dec. 2020.

[17] W. Tang, T. Li, and W. Zhan, "Coordinated control of photovoltaic and energy storage system in low-voltage distribution networks based on three-phase four-wire optimal power flow," (in Chinese), *Autom. Electric Power Syst.*, vol. 44, no. 12, pp. 31–42, Jun. 2020.

[18] H. Wang, J. Zhao, Q. S. An, and L. G. Kang, "Study on optimization and policy incentives of distributed energy system under different building loads," (in Chinese), *Proc. CSEE*, vol. 35, no. 14, pp. 3734–3740, Jul. 2015.
[19] M. Elkazaz, M. Sumner, E. Naghiyev, S. Pholboon, R. Davies, and D. Thomas, "A hierarchical two-stage energy management for a home microgrid using model predictive and real-time controllers," *Appl. Energy*, vol. 269, Jul. 2020, Art. no. 115118, doi: 10.1016/j.apenergy.2020.115118.
[20] Z. Jiang and J. Chen, "Optimal distributed generator allocation method considering uncertainties and requirements of different investment entities," (in Chinese), *Proc. CSEE*, vol. 33, no. 31, pp. 34–42, Nov. 2013.
[21] Z. Liu, B. Wang, and K. Tang, "Handling constrained multiobjective optimization problems via bidirectional coevolution," *IEEE Trans. Cybern.*, vol. 52, no. 10, pp. 10163–10176, Oct. 2022, doi: 10.1109/TCYB.2021.3056176.
[22] Y. Ju, H. Li, and Z. Yu, "Bi-level robust capacity planning of micro-grid considering multivariate uncertainties and reserve demand," *Power Syst. Technol.*, vol. 2022, pp. 1–20, Jun. 2022, doi: 10.13335/j.1000-3673.pst.2022.0555.

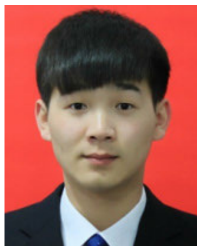
YU FU was born in Guizhou, in 1980. He received the B.S. and M.S. degrees in electrical engineering from Guizhou University, in 2001 and 2006, respectively. He has been the Head of the Distributed Power Network Department, Power Science Research Institute, Guizhou Power Grid Company Ltd., China, since 2021.

YANG WANG was born in Guizhou, in 1980. He received the B.S. and M.S. degrees in electrical engineering from Guizhou University, in 2001 and 2006, respectively. He has been the Deputy Dean of the Distributed Power Network Department, Power Science Research Institute, Guizhou Power Grid Company Ltd., China, since 2021.

YONGXIANG CAI (Member, IEEE) was born in Guizhou, China, in 1982. He received the Ph.D. degree in electrical engineering from China Agricultural University, in 2019. He has been a Key Member of the LVDN Group, Distributed Power Network Department, Power Science Research Institute, Guizhou Power Grid Company Ltd., China.

ANJIANG LIU received the M.Sc. degree in electrical engineering from Guizhou University, in 2016. He is currently with the Power Science Research Institute, Guizhou Power Grid Company Ltd., China.

YI WEN was born in Guizhou, in 1972. He received the B.S. degree in electrical engineering from Shanghai Jiaotong University, in 1994. He is currently the Head of the Power Science Research Institute, Guizhou Power Grid Company Ltd., China.



HONGWEI LI was born in 1992. He received the B.S. degree in electrical engineering from the Harbin University of Science and Technology, in 2016. As a filed engineer, he is currently with Qingdao Topscomm Communication Company Ltd., China.

JIAKUAN REN is currently with the Power Science Research Institute, Guizhou Power Grid Company Ltd., China.

YANGQUAN QU received the M.Sc. degree in electrical engineering from Guizhou University, in 2016. He is currently with the Power Science Research Institute, Guizhou Power Grid Company Ltd., China.