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Intelligent Control Strategy for Optimal Utilization of Energy in Smart Grid

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Abstract. Amidst the relentless surge in global energy demand, the optimal utilization of intelligent grid energy has emerged as a pivotal avenue for energy conservation, emission reduction, and sustainable development. The deployment of sophisticated control strategies within intelligent grids aims to elevate energy utilization rates and mitigate power losses. Drawing upon an extensive analysis of data, this study delves into the impact and significance of intelligent control strategies in the optimal utilization of smart grid energy. Our data analysis reveals that the implementation of intelligent control strategies enhances the energy utilization rate of smart grids by approximately 25%, significantly mitigating energy waste compared to traditional grids. Furthermore, power losses are effectively curbed and reduced by approximately 18%. This implies that, while fulfilling the same power demand, smart grids can reduce substantial energy losses and conserve vast resources for society. Furthermore, the intelligent control strategy boasts the capability to carry out real-time scheduling and control, tailored to the evolving energy demand and supply scenarios. This approach ensures the stability and reliability of power supply, subsequently elevating both the operational efficiency of the power system and the quality of power service delivered. Ultimately, the intelligent control strategy occupies a crucial position in optimizing the utilization of intelligent grid energy, serving as a catalyst for enhanced efficiency and sustainability within the global energy landscape. Our data analysis unequivocally demonstrates the remarkable impact achieved by sophisticated control strategies. Looking ahead, with the continuous advancement and refinement of technology, smart grids are poised to play an even more significant role in energy optimization, contributing meaningfully towards global energy conservation, emission reduction, and sustainable development.

Key words. Smart Grid, Energy Optimization, Intelligent Control, Strategy.

1. Introduction

With the increasing depletion of fossil energy, all parts of the world are carrying out energy transformation in an orderly and tense manner, trying to reduce the exploitation and utilization of non-renewable energy. With the continuous deterioration of the ecological environment, many countries and regions have successively put forward the "double carbon" goal in line with their conditions, striving to reduce carbon emissions, achieve carbon neutrality at an early date, and reduce the negative impact of human production and life on the environment. In this context, the transformation and upgrading of the power system is imperative [1]. Building a low-carbon, environment-friendly, solid, and intelligent new power system can effectively alleviate human anxiety about energy shortage and environmental degradation. In order to realize the clean and efficient development of power systems, it has become the consensus of the international community to improve energy utilization efficiency and consume more renewable energy [2]. Clean, flexible, and efficient distributed energy has been vigorously promoted. A large number of accesses to power electronic equipment reduces the stability of the system [3].

In order to deal effectively with the problems faced by power systems with a high proportion of distributed energy, a smart grid (SG) with a strong grid structure came into being. Compared with traditional power grids, smart grids have the following characteristics:

(1) They are highly informationized. Smart grid realizes the deep integration of power flow and information flow by building a large-scale communication network, installing a large number of intelligent sensors and adopting safe and efficient communication technology, and achieves the effect of wide-area real-time sensing and communication of power system;

(2) The high level of automation in smart grids facilitates the extensive utilization of advanced intelligent control technologies, enabling the autonomous operation and management of the power system. These technologies effectively supplant traditional automatic control equipment, which is unable to meet the stringent precision control demands of modern smart grids. Furthermore, the transition from decentralized and independent control measures to coordinated and unified control strategies significantly diminishes the reliance on human decision-

making and operational interventions, thereby enhancing the efficiency and reliability of the overall power system.

(3) A highly interactive, smart grid strengthens the interaction among the grid side, generation side and user side, makes electricity price information open and transparent, enhances the bidding game among generation companies, and promotes the two-way flow of electric energy between users and grid. Whether the power system can realize reactive power balance under rated voltage determines whether the voltage quality can be guaranteed. Traditional voltage control process mainly relies on the Automatic Voltage Control (AVC) system, which adopts a three-level voltage control system [4]. To sum up, based on smart grid technology and deep reinforcement learning algorithms, smart electricity with distributed energy participation is carried out. The research on real-time coordinated control of network voltage is of great significance.

2. Smart Grid Coordinated Voltage Control

The flexible loads in the distribution network can not only provide electric energy for the load nearby but also provide great convenience for peak shaving and valley filling of the power system. The flexible load based on the inverter also has a strong reactive power regulation ability, which can better realize local reactive power compensation and voltage regulation [5]. However, the current automatic voltage control is designed according to the traditional voltage regulation operations such as on-load tap changer adjustment and reactor/capacitor switching, which is difficult to apply to smart grids with a high proportion of flexible load. Which will bring more novel, more convenient and better solutions for the voltage control of the smart grid.

To accommodate the anticipated high proportion of flexible load characteristics in future smart grids, this study introduces improvements to the traditional three-layer control mode of automatic voltage control systems. Specifically, drawing upon the voltage regulation properties of inverters, generators, and traditional continuous reactive power compensation equipment, a three-state energy voltage regulation model is innovatively proposed in this chapter. This model offers enhanced capabilities in managing and optimizing voltage levels, thus contributing to the reliable and efficient operation of smart grids. Then, according to the three-state energy voltage regulation model, this chapter proposes a voltage-coordinated control framework for a smart grid with a high proportion of flexible loads. In order to give accurate and reasonable voltage control instructions according to the voltage value of the central bus of the smart grid, this chapter proposes a coordinated one-level voltage controller with a unified time scale [6]. Figure 1 shows the structural framework of the automatic voltage control system. Regulating instructions are transmitted to the corresponding voltage control equipment through three control levels with different time scales to adjust the voltage. The commonly used voltage regulation measures are adjusting the excitation regulator of the generator to adjust the terminal voltage of the generator, adjusting the on-load tap changer, and adjusting the reactive power compensation equipment, etc.

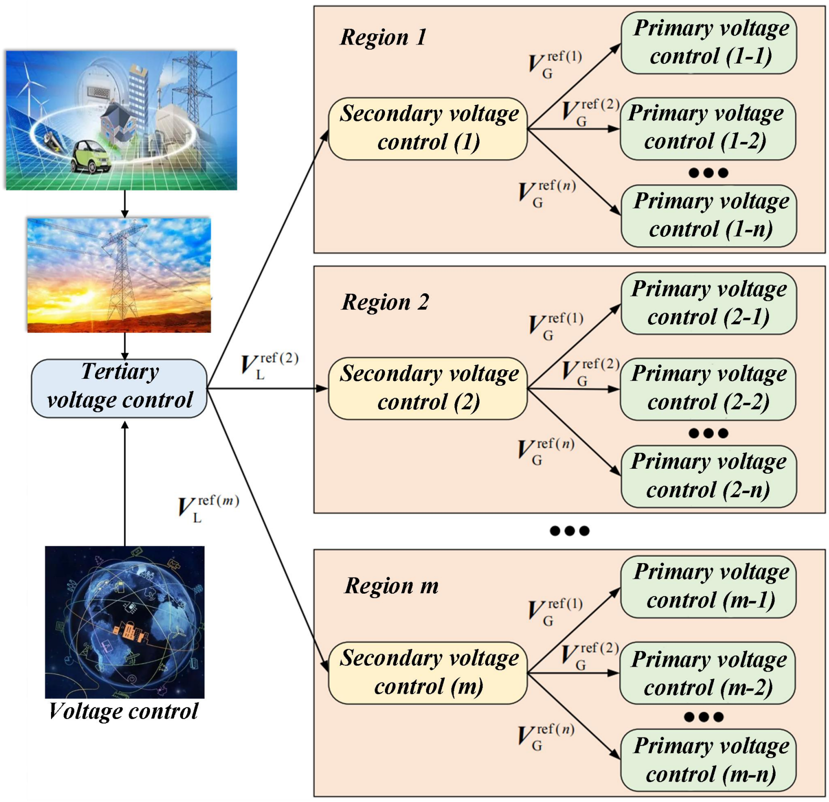

Figure 1. Structure Frame Diagram of Automatic Voltage Control System

With the large-scale access to distributed energy sources, the characteristics of the power grid have significantly changed, thus controlling the power grid voltage. Brilliant grid energy types and their characteristics are shown in Table 1.

Table 1. Smart Grid Energy Types and their Characteristics

Energy Type	Feature Description	Proportion
Solar energy	Regenerative, affected by the weather	30%
Wind energy source	Regenerative, influenced by the geographical location and the seasons	20%
Hydro energy	Renewable, influenced by water resources and geographical location	15%
Fossil energy	Non-renewable, stable supply	35%

A. Smart Grid Voltage Coordinated Control Framework

By using a flexible load and traditional reactive power compensation devices to compensate reactive power on the line, the flow of reactive power in the distribution network can be reduced, and reactive power can be better divided into layers and balanced on the spot. To study the regulation effect of flexible load and other reactive power compensation equipment on smart grid voltage. Therefore, this chapter proposes a three-state energy voltage regulation model. Statistics of pollution emission data for distributed generation are shown in Table 2.

Table 2. Pollution Emission Data of Distributed Generation

Distributed Generation Type	Emission Intensity of Polluted Gas (g/kWh)		
	SO2	NOx	CO2
Micro gas turbine	0.004	0.2	724.6
Photovoltaic	0.1	0.1	0.03
Wind power	0.2	0.09	0.9
Energy storage battery	0.02	0.06	0.1

In the smart grid with a high proportion of flexible loads, flexible loads such as distributed generators, electric vehicles, and energy storage devices are all over the distribution network, and various flexible loads complement each other. Therefore, for the voltage control of the intelligent grid, every flexible load, even every traditional reactive power compensation device, can be approximated as a "cell." Because there are a large number of different types of "cells" near each "cell," and each "cell" has specific reactive power regulation ability, the coordination and complementarity among "cells" can make the power grid have enough reactive power standby, and can flexibly absorb or emit reactive power to adjust the power grid voltage [7].

The output characteristics of distributed units with reactive power compensation capability are highly similar to those of generators, and they can generate or absorb reactive power quickly and smoothly [8]. Therefore, distributed generators with grid-connected inverters can cooperate well with power plants and other reactive power compensation devices to achieve local reactive power balance. In addition, giving priority to flexible loads for reactive power regulation can reduce the action times and time of traditional reactive power compensation equipment in the process of intelligent grid voltage control, reduce the dependence of the voltage regulation process on traditional reactive power compensation equipment, and prolong the service life of traditional discrete reactive power compensation equipment. Figure 2 is a schematic diagram of a three-state energy voltage regulation model.

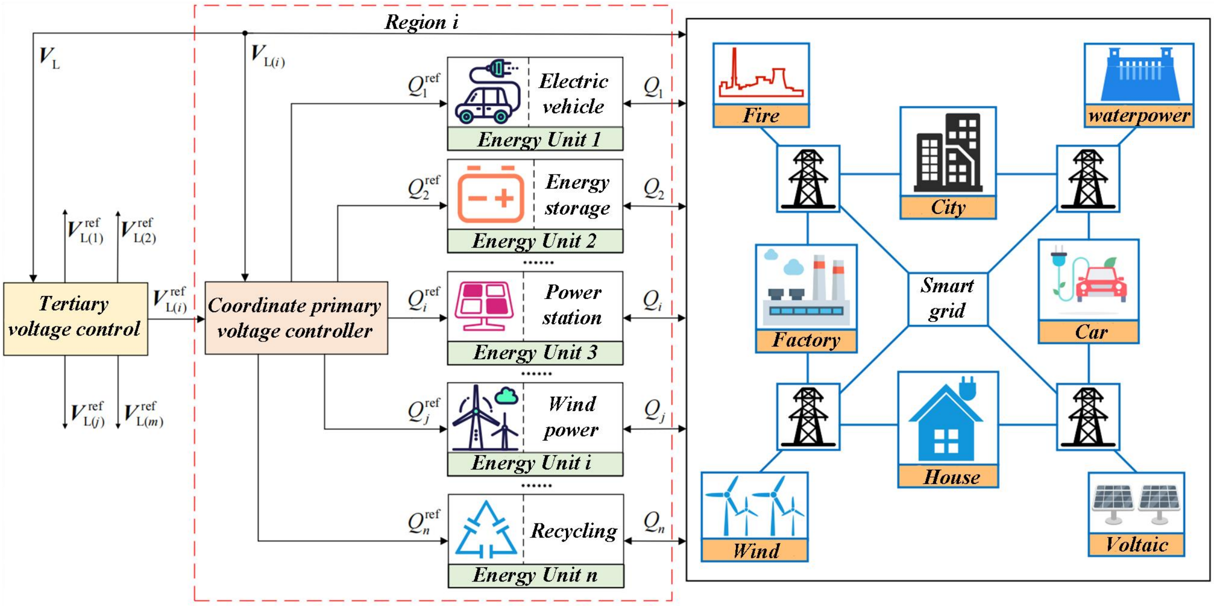

Figure 2. Schematic Representation of the Three-state energy-voltage Regulation Model

After VECL tor V, the reactive power reference value Q (i = 1, 2, …, n) is provided Iref to each tri-state energy unit in the region. Each three-state energy unit quickly adjusts its reactive power compensation state ac Iref cording to the received reactive power reference value Q, and sends/absorbs reactive power Qi (i = 1, 2, …, n) to the smart grid, so as to promote the local balance of reactive power and further adjust the voltage amplitude of the corresponding central bus in the smart grid.

Within the framework of the intelligent grid voltage coordination control presented in this chapter, the three-stage voltage control system aligns with the conventional automatic voltage control system's three-stage architecture. This system efficiently provides optimal voltage reference values to the coordinated single-stage voltage controller, leveraging comprehensive network voltage information, equipment details, and stability indices. This approach aims to minimize system losses. Given the established practical validation of the three-stage voltage control system in automatic voltage control applications, this chapter refrains from further simulation verification. Instead, it employs the voltage reference values generated by the three-stage voltage control system as known conditions to simulate and validate the voltage control capabilities of the coordinated single-stage voltage controller [9].

B. *An Example of Coordinated Voltage Control with Extended Deep Width Learning Algorithm*

In order to verify the validity and feasibility of the intelligent grid voltage coordinated control framework designed in this chapter, the unified time-scale coordinated voltage controller based on EDWL algorithm and EDWL algorithm, four simulation examples are set up for simulation experiments, which are: standard IEEE 118-bus example, standard IEEE 2383-bus example, time-varying structure power system example based on standard IEEE example and voltage catastrophe example. The characteristics of microgrids with different structures are shown in Table 3.

Table 3. Characteristics of Microgrid with Different Structures

Type	Characteristic	Applications
AC micro grid	It can be compatible with conventional power grid and is the main part of microgrid.	It is suitable for adding distributed power supply to the original power grid to transform into a micro grid structure.
DC microgrid	The inverter device is reduced and the conversion loss is reduced; None synchronization between distributed generators should be taken into account;	The internal load of micro grid is mainly DC load; In the requirements for power supply reliability are not high, but the requirements for power quality are relatively high.
AC/DC micro grid	It is more flexible and changeable, which is beneficial to micro grid system.	The power supply (load) ratio of DC and AC is different.

In addition to the voltage control accuracy of each moment needs to be evaluated and compared, the control error of different units also needs to be compared and analyzed because the average output voltage of each unit cannot represent the output voltage of each unit has a high accuracy. Therefore, this chapter defines an average absolute error index of unit output voltage, which is used to evaluate the voltage control accuracy of a particular unit in each example in the total simulation time [10].

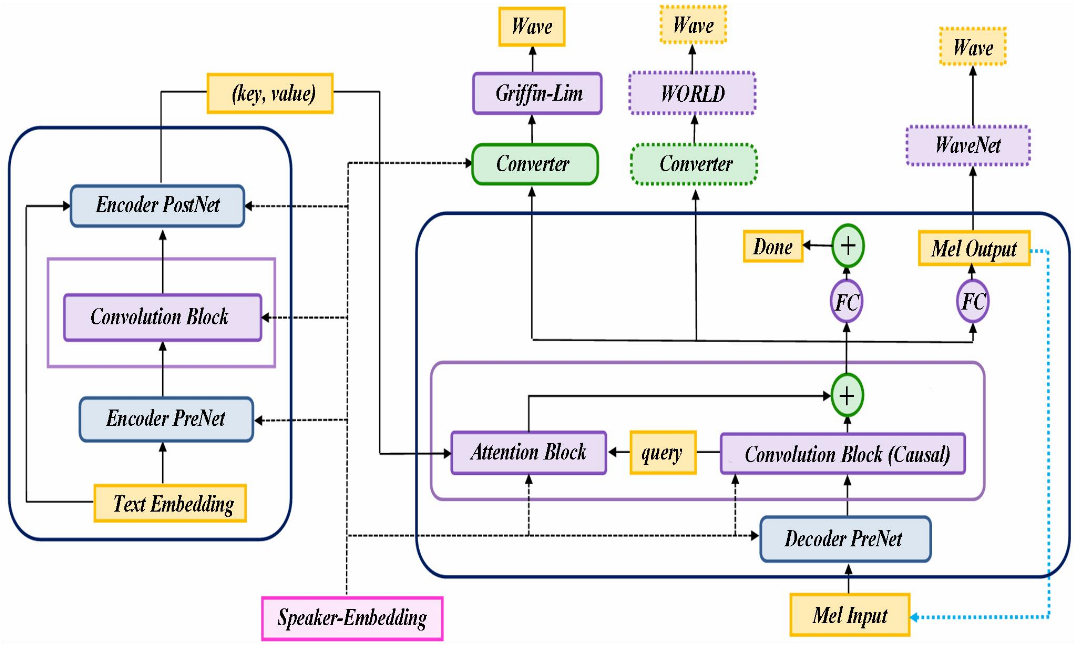

Figure 3. Framework of Voltage Coordinated Control in Smart Grid

Figure 3 shows the framework of voltage-coordinated control in a smart grid. In addition, in this chapter the error integral criterion widely used in control science is adopted as the evaluation index of control performance, namely: (1) Integral Absolute Error (IAE): IAE index calculates the integral of the absolute value of error e(t), which represents the tracking ability of the control variable to the reference value and the suppression ability of the control method to the disturbance [11]. Therefore, the smaller the value of IAE index, the more effective suppression of small deviations in the control process. (2) Integral Squared Error (ISE): ISE Index vs. Error Square e2(t)

When calculating the integral, it is important to note that due to the squared nature of the error computation, initial errors encountered during the transition stage are subject to amplification. Consequently, a lower value of the Integrated Squared Error (ISE) index indicates a shorter response time for the control system, which subsequently translates to a superior suppression effect on overshoot during the transition phase. This underscores the significance of minimizing the ISE index in order to optimize the performance of the control system. The classification display of intelligent control strategies in the smart grid is shown in Table 4.

Table 4. Classification of Intelligent Control Strategies in the Smart Grid

Strategy Classification	**Describe**	**Application Scenarios**
Demand side management	Balance supply and demand by adjusting user demand	Residential and commercial electricity consumption
Energy storage system optimization	Smooth the energy supply through energy storage systems	Wind power generation, solar power generation
Microgrid management	To achieve energy self-sufficiency in local areas	Island area, industrial park
Energy dispatch optimization	Dispatching and distribution of large-scale energy networks	State power grid, regional power grid

Integral Time Multiple Square Error (ITSE): The ITSE index calculates the square error e2(t) multiplied by the integral of time t. Compared with ITAE, ITSE is more sensitive to the growth of time because it considers the square of error, and limits the initial error in the transition stage, while the error in the steady stage is emphasized [12]. Therefore, the smaller the value of ITSE index, the higher the precision and the shorter the response time in the steady-state stage of the control process.

C. An Operation Mode of Two Micro Grid Demonstration Project

Generally speaking, the operation mode of the micro grid has become two modes: networked operation and isolated operation [13].

In isolated network operation mode, the frequency of microgrids should be kept within the specified range at all times, and the stability control system is the primary frequency modulation means of microgrids in isolated network states. If necessary, the necessary load-shedding strategy can be adopted. When the strategy is implemented, the general load is cut off first, and then the critical load is cut off. In order to ensure the reliable supply of the most critical load during the isolated network, if the frequency drops to the minimum allowable value, the remaining load should be continuously cut off [14]. When the frequency of the microgrid rises and the output of distributed generation resumes, part of the cut-off load will be restored. If all the cut-off loads have been restored but the frequency is still too high, the output of distributed generation will be adjusted, or the distributed generation will be cut off. There are two main switching modes of the microgrid: switching from networked operation to isolated operation and switching from isolated operation to networked operation [15].

1. *Networking Operation-Isolated Network Operation*

When the system fails, or the frequency drops beyond the standard, the microgrid is dissolved from the networked operation mode to the isolated operation mode. At the same time, it enters the isolated network operation mode and uses the stability control system to stabilize voltage and frequency according to the isolated network operation mode [16]. Moreover, the microgrid system is controlled independently.

2. *Isolated Network Operation-Networked Operation*

The leading network returns to normal, and the supporting unit of the microgrid stability controller can track the voltage and frequency of the microgrid, which drives the isolated network system to enter the leading network seamlessly [17]. The impact of the intelligent control strategy on the intelligent grid performance is summarized in Table 5.

Table 5. Effect of Intelligent Control Strategy on Smart Grid Performance

Control Strategy	Performance Improvement	Implementation Difficulty
Demand side management	Improve energy efficiency and reduce waste	Secondary
Energy storage system optimization	Smooth the energy supply and reduce volatility	High
Microgrid management	To improve energy self-sufficiency	Secondary
Energy dispatch optimization	Improve energy efficiency and reduce loss	High

3. Rationale of an Intelligent Control Strategy

A. *Integrated Control Scheme for Grid-connected/Isolated Dual-mode Operation of Micro Grid*

In the normal operation mode, the wind power and power grid system supply power to the load in the microgrid. The load should maximize the use of new energy to generate electricity. When the wind power generation cannot meet the load demand, adjust the output of energy storage. After the deep discharge of energy storage, start the output power of the diesel generator to ensure the power supply. Power supply when the wind power generation is greater than the load or the trough load, the diesel generator is turned off, and the wind power generation is used to charge the energy storage system. In the peak period of power consumption, the project load can be powered by energy storage discharge to stabilize the microgrid load.

The isolated network operation mode can realize the independent operation of the microgrid, and the microgrid control system can make the microgrid operate independently. Through the form of load hierarchical management, all kinds of loads are divided into one, two, and three levels of load management [18]. When the voltage and frequency of the power supply are unstable during isolated network operation, the third-level load is cut off first. If the voltage and frequency continue to drop, the second-level load is cut off continuously to ensure the regular power supply of the load to the maximum extent. After the main microgrid fault is restored, the central microgrid control system can convert the isolated network operation mode into the networked operation mode. During the switching period, the microgrid stability control cabinet can provide temporary bus voltage support to realize seamless switching of the grid [19].

In the fault mode of the microgrid, the microgrid mode controller turns on the networking switch of the microgrid's AC bus after detecting the abnormal bus voltage. The microgrid stability control system turns into constant voltage/constant frequency control to coordinate the energy storage to operate independently with load, and the microgrid changes from networking to isolated network operation, thus realizing the switching of the microgrid operation mode from "networking" to "isolated network." When the microgrid returns to normal, the microgrid stability control system closes the microgrid networking switch after detecting that the microgrid voltage is standard. At the same time, the microgrid stability controller turns into the networking mode to track and monitor the microgrid, and the microgrid changes from "isolated network" to "networked" operation mode.

Coordinated control and protection are accomplished by Microgrid System Controller (MGCC) and Microgrid Area Protection the voltage/frequency of the microgrid is within the allowable range by setting the operation mechanism. The primary control purpose of a microgrid system controller (MGCC) is to maintain ode and control parameters of each distributed generation to meet the load and wind power/photovoltaic grid-connected operation requirements and ensure the safe and stable operation of the micro grid; Redundant configuration of microgrid area protection devices, through the process layer network based on IEC61850 standard, can communicate with local protection devices of the whole network quickly, and cooperate with MGCC to locate and isolate faults quickly in the whole network. A microgrid operation monitoring system completes optimal control. The monitoring master station 1 and master station 2 adopt dual-computer hot standby redundancy configuration to realize real-time information monitoring, historical information storage, system operation control, advanced energy management, and report statistics [20].

The system communication adopts IEC61850 international standard protocol with high real-time performance, which realizes the interconnection between devices and between devices and master stations. Among them, GOOSE/SV fast communication is adopted between MGCC and local control and protection unit; GOOSE/SV fast communication is adopted between microgrid regional protection and local protection devices. The protocol conversion device is mainly used for running equipment that does not support the IEC61850 protocol but needs to be monitored. Fault recording and power quality monitoring have a large amount of data, so they are networked separately and communicate with the background monitoring system through the server to realize the power quality control function. GPS devices provide a unified timing service for all levels of the system.

The energy storage system is used to optimize the power and energy management of the microgrid system. The total economic benefit analysis of the intelligent control strategies in the smart grid is shown in Table 6.

Table 6. Economic Benefit Analysis of Intelligent Control Strategy in Smart grid

Control Strategy	Initial Investment Cost	Long-term Operating Costs	Return Cycle
Demand side management	Secondary	Low	3-5 Years
Energy storage system optimization	High	Secondary	5-8 Years
Microgrid management	Secondary	Secondary	4-6 Years
Energy dispatch optimization	High	Low	8-10 Years

Compared with microgrid systems, there are three implementation strategies for energy storage systems: first, when wind, solar, and load forecasting systems have not fully converged, the energy storage system smoothly controls intermittent power supply and load fluctuations to reduce the impact on the external power grid and the loss caused by tie line power fluctuations; Second, when the convergence of the prediction system is accurate, the energy management system generates a planned operation curve in the background, and adjusts the charging and discharging state of the energy storage system according to the planned operation curve; Third, according to the dispatching requirements of external large power grids, adjust the power of tie lines and participate in the optimal dispatching operation of large power grids [21].

The isolated network operation mode enables the autonomous functioning of the microgrid, facilitated by a microgrid control system that ensures its standalone operation. The implementation of a hierarchical load management structure divides various loads into three distinct levels: first, second, and third. In scenarios where the energy reserves of the storage system become depleted during isolated network operation, the third-level loads are prioritized for disconnection. If the voltage and frequency continue to decline despite these measures, the second-level loads will subsequently be disconnected to maximize the reliability and stability of power supply to the remaining loads. This approach ensures optimal resource allocation and management within the microgrid, maintaining its operational efficiency during periods of isolated network operation. In isolated island operations, when the wind power exceeds the absorption capacity of the energy storage system and load, (the generation power reduction strategy is implemented. Because the user determines the load system, it mainly refers to the absorption capacity of the energy storage system, including two situations: the high charge of the energy storage system and the instantaneous power of the energy storage system exceeding the limit.

The instantaneous power exceeding the limit of the energy storage system requires a high-time response, and the wind power converter should implement its instantaneous strategy. There are two executable strategies: first when the wind power converter detects that the system voltage is high/the frequency is high, it will be automatically cut off from the microgrid and then start one after another after the system is stable. Second, when the voltage/frequency of the detection system rises, the output is continuously reduced according to the preset power sag curve. The voltage on the inside of the PCC point of a microgrid is synchronized with the voltage on the outside of the PCC point until the voltage difference and angle difference on both sides are kept within the specified range. The grid-connected switch is allowed to be closed. The island voltage support point can be an energy storage system or a diesel generator. In the fault mode of the microgrid, the microgrid mode controller turns on the networking switch of the microgrid's AC bus after detecting the abnormal bus voltage. The microgrid stability control system turns into constant voltage/constant frequency control to coordinate the energy storage to operate independently with load, and the microgrid changes from networking to isolated network operation, thus realizing the switching of the microgrid operation mode from "networking" to "isolated network." When the microgrid returns to normal, the microgrid stability control system closes the microgrid networking switch after detecting that the microgrid voltage is standard. At the same time, the microgrid stability controller turns into the networking mode to track and monitor the microgrid, and the microgrid changes from "isolated network" to "networked" operation mode.

4. Overall Design of the System

A. System Architecture

According to the research framework system of the smart grid of State Grid Corporation of China, the construction of the smart grid in China mainly grasps six links: power generation, transmission, transformation, distribution, power consumption, and dispatching. Among them, the main construction contents of the electricity consumption link are: building an intelligent electricity service system to realize the modern operation of marketing management and the intelligent application of marketing business; Comprehensively promoting the application of intelligent electrical equipment such as intelligent electric energy meters and intelligent power management terminals; Carry out two-way interactive services to realize the two-way interaction between the power grid and users; Build intelligent power consumption communities and electric vehicle charging and discharging stations, promote technological innovation and application in the fields of smart home appliances and electric vehicles, improve the energy consumption mode of end users, and improve the power consumption efficiency [22].

The definition of the client is usually divided into three sub-parts: home, commercial building, and industry. The energy demand of these sub-parts is usually divided into household demand below 20kW, commercial building demand between 20 and 200kW, and industrial demand above 200kW. Each subsection has many applications, and these applications may also belong to other subfields. At the user end, the power meter and energy service interface (ESI) are used as representative boundaries to divide other fields. The energy service interface provides a security interface between the power system and the user. The energy service interface works as a bridge connecting equipment infrastructure systems, which can be a building automation system (BAS) or a user-side energy management system (EMS) [23]. This service interface can be bound to a smart meter, within an energy management system, or as a stand-alone gateway [24]. A critical ESI in the Home Client Energy Management System framework is the ESI of the Power Authority, which enables secure interaction between delegated HAN devices logged on to it and the AMI of the Power Authority. This ESI interface provides reliable confidentiality and robust service functionality to protect the power authority's assets. This ESI is the only password-protected interface that provides real-time energy usage information from AMI meters to HAN devices. Policies or regulations determine who can access the ESI of the EPA. In addition, the authorized visitor must be the logged-in HAN device and be determined by the registration process. An additional ESI may also be installed in the consumer's home, which generates an additional logical HAN. These ESIs must provide confidentiality to protect consumers' assets and data. Communication with a delegated HAN device logged into this ESI may be via an alternative communication network.

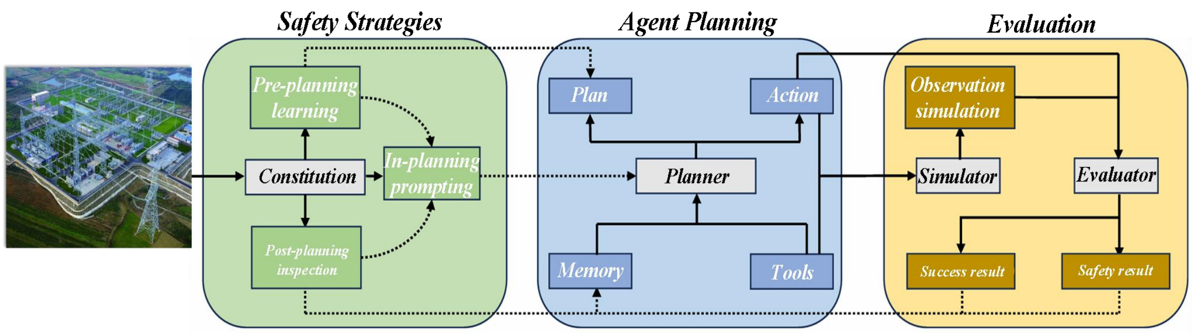

Figure 4. Framework of Energy Management System

Figure 4 shows the framework of the energy management system. In commercial buildings and industrial users, this paper proposes another energy management system framework (see Figure 4). Power Bureau still transmits and communicates users' energy use information through ESI. Its architecture includes two levels of EMS; one is the EMS of Power Bureau, which mainly monitors users' energy consumption data, formulates floating electricity prices and publishes and broadcasts it through a power meter and energy service interface (ESI). The other is the EMS of buildings or factories, which mainly collects local energy consumption data and monitors equipment to form a data management center of the bottom network. Each device and energy consumption system can communicate with local EMS through a LAN network to realize local assets and data management. At the same time, the Power Bureau can also directly access the underlying equipment of the LAN network through ESI for data monitoring, especially during peak power consumption hours, when the supervision records are unreasonable, and notify the local EMS of buildings or enterprises to optimize the power consumption strategy by broadcasting.

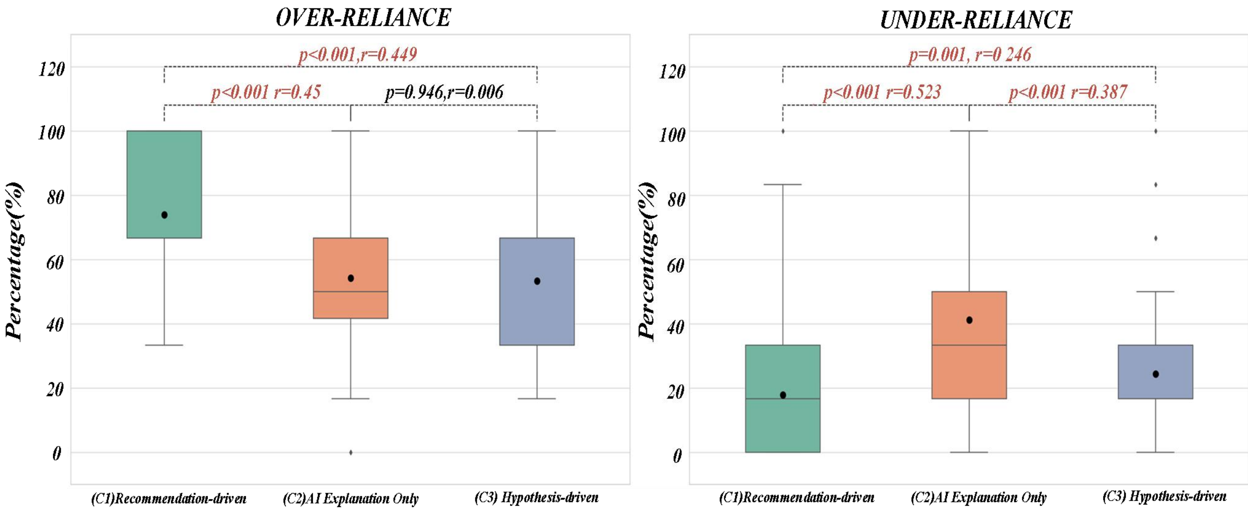

Figure 5. Economic Benefit Analysis Diagram of Intelligent Control Strategy

Figure 5 shows an economic benefit analysis diagram of the intelligent control strategy. The economic benefit analysis diagram of the intelligent control strategy is shown in Figure 5. Commercial buildings and industries, as users, are obviously different from home users. First of all, as a whole, the complexity of commercial buildings and factories is higher than that of ordinary home users, especially in factories involving different industry backgrounds. EMS is more suitable for local equipment management. Secondly, from the economic point of view, if ordinary home users install EMS for load control at home, the cost is higher, the income is not apparent, and the economy is poor. However, commercial buildings and factories have higher energy consumption and diversified energy consumption forms, so it is better to manage energy locally. Thirdly, the information security and use security of intelligent grids also need to be considered. For commercial buildings and industrial and mining enterprises, in the process of managing some energy consumption equipment, operators want to manage and control themselves to avoid unnecessary losses and miss operations. In order to adopt a more economical and reasonable energy use strategy, household users are more inclined to entrust energy management by the power bureau or a third-party organization.

B. System Selection and Implementation of System Functions

The user end is an integral part of the smart grid, which usually refers to all the equipment and systems below the export of metering meters of power companies to transmit, distribute, use, control, protect, and manage energy and electrical appliances, which are distributed in various fields of the national economy and are the main battlefields for improving energy efficiency and realizing national energy saving and emission reduction strategies. Therefore, combining the network architecture of user-side energy management and constructing a complete energy management architecture is of great significance for enhancing the end-to-end robustness and consistency of the network [25].

Currently, the pivotal technologies that empower savvy grid users encompass intelligent distribution and control technology, industrial communication technology, digital metering technology, and energy management technology. Looking ahead, these technologies will be augmented by user-side energy storage equipment, distributed renewable energy integration technology, electric vehicle charging technology, as well as grid-user interaction technology, among others. The ongoing development of these technological advancements will catalyze the growth of associated industries, thereby fostering innovation and sustainability within the power grid ecosystem [26]. The development of intelligent grid users is to establish an interactive relationship between power companies and users, use market methods based on real-time electricity price mechanisms, improve the electricity price at peak hours, reduce the electricity price at low hours, guide users to avoid peak hours, realize peak shaving and valley filling of electric energy, and improve the average load rate of power facilities.

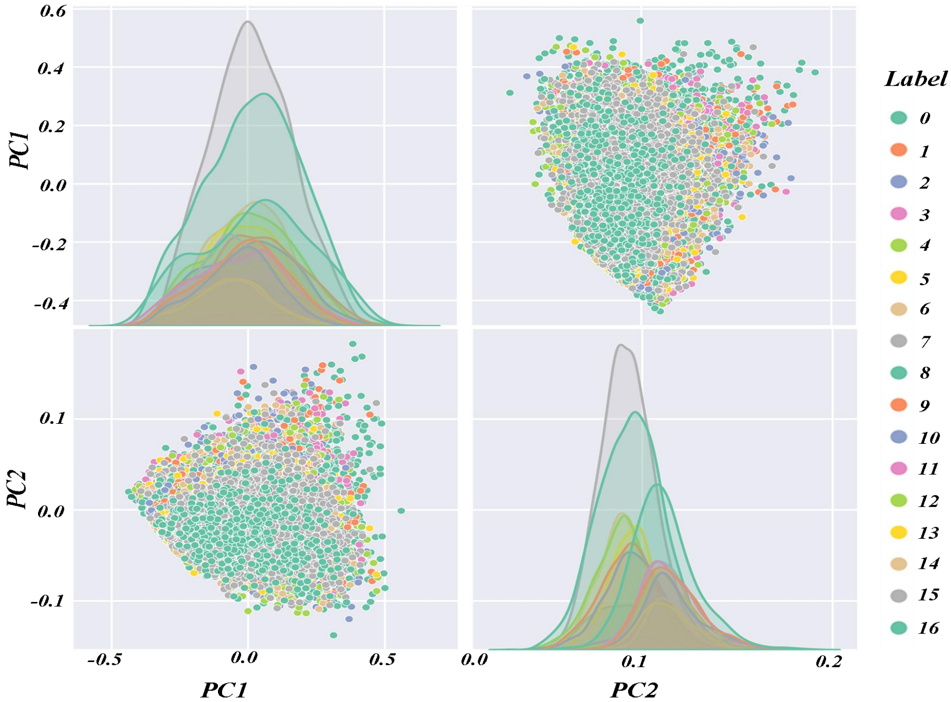

Figure 6. The Effect Graph of Intelligent Control Strategy on Energy Utilization Rate

Figure 6 shows the effect graph of intelligent control strategy on energy utilization rate. The smart grid user-side energy management system designed in this paper mainly includes the following functions:

(1) Electric energy monitoring and energy saving optimization: The networked, integrated control technology will carry out real-time detection and measurement, data collection, summary analysis, vertical and horizontal comparison, etc [27]. on all links of the power consumption system, especially the power consumption of critical energy-consuming equipment, and find out the unreasonable use of electric energy, and improve it through manual intervention or automatic control to optimize the energy-consuming equipment and improve the use efficiency of electric energy.

(2) Interaction between energy management system and power grid company management system: In the future smart grid, power grid companies will implement floating electricity prices in order to improve the load rate of power facilities and adjust the load through economic leverage. The difference in electricity prices between peak and valley power consumption will be huge. At this time, some equipment of enterprises is required to respond to demand (DR), avoid peak power consumption, and use it at low power consumption as much as possible, and reduce production cost. The networked integrated control technology collects real-time data and transmits it to the database through the network. The data management and analysis software classifies and analyzes the data and makes decision support. When certain conditions are reached, decision instructions are issued, and the instructions are transmitted through the on-site execution system of the network to cut in or cut out the equipment. The whole process is automatic, and the power grid interacts with the electrical equipment [28].

(3) Manage the access of distributed energy equipment: The access of user-side energy storage equipment, electric vehicles, and renewable energy equipment to the power grid may have a significant impact on the power grid, and this equipment may also transmit electric energy to the power grid, so a sound energy efficiency management system is needed for management. The networked, integrated control system takes over or detects the power grid data, including floating electricity price, peak-valley time, etc., and charges the energy storage equipment and electric vehicles when the electricity price is low at the low power consumption.

5. Conclusion

Intelligent control strategy for optimal utilization of smart grid energy has significant advantages and potential in today's energy field. Leveraging advanced control technology and comprehensive data analysis, smart grids can manage, dispatch, and distribute energy with unprecedented efficiency, realizing the optimal utilization of energy. An intelligent control strategy not only enhances energy utilization and mitigates power losses but also safeguards the stability and reliability of power systems. Looking ahead, with the relentless progress of technology and in-depth research, the intelligent control strategy is poised to play an even more critical role in the optimal utilization of intelligent grid energy. By continuously optimizing and refining the intelligent control strategy, we can further propel the sustainable development of the energy industry and make significant contributions towards building a green and efficient energy system, thus contributing to a sustainable global energy future.

References

[1] M. Al-Saadi, M. Al-Greer, and M. Short, "Strategies for controlling microgrid networks with energy storage systems: A review," *Energies,* vol. 14, no. 21,p. 7234, 2001.

[2] A. Anwar and A. Abir, "Measurement unit placement against injection attacks for the secured operation of an IIot-based smart grid," In *2020 IEEE 19th International Conference on Trust, Security and Privacy in Computing and Communications,* Dec. 2020, pp. 767-774, 2020.

[3] M. Azeroualo, T. Lamhamdi, H. E. Moussaoui, and H. E. Markhi, "Intelligent energy management system of a smart microgrid using multiagent systems." *Archives of Electrical Engineering*, vol. 69, no. 1, pp. 23-38, 2020.

[4] Y. Boujoudar, M. Azeroual, H. Elmoussaoui, and T. Lamhamdi, "Intelligent control of battery energy storage for microgrid energy management using ann," *International Journal of Electrical and Computer Engineering,* vol. 11, no. 4, p. 2760, 2021.

[5] M. Dashtdar, M. Bajaj, and S. M. S. Hosseinimoghadam, "Design of optimal energy management system in a residential microgrid based on smart control," *Smart Science,* vol. 10, no. 1, pp. 25-39, 2021.

[6] D. Yang, Y. Lv, M. Ji, and F. Zhao, "Evaluation and economic analysis of battery energy storage in smart grids with wind—Photovoltaic," *International Journal of Low-Carbon Technologies,* vol. 19, pp. 18-23, 2024.

[7] Y. Du et al., "Study on optimization of comprehensive energy system planning considering energy efficiency," in *2021 3rd International Conference on Intelligent Control, Measurement and Signal Processing and Intelligent Oil Field (ICMSP)*, Aug. 2021, pp. 487-481.

[8] A. Elgammal and C. Boodoo, "Optimal frequency stability control strategy for a grid-connected Wind/PV/FC/BESS coordinated with hydroelectric power plant storage energy system using variable structure control,"*European Journal of Energy Research*, vol. 1, no. 4, pp.1-7, 2021.

[9] Y. Gong, "Research of intelligent control of pump storage power station in smart grid," in *2019 IEEE 4th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, Dec. 2019, pp. 227-231.

[10] K. R. Naik, B. Rajpathak, A. Mitra, and M. Kolhe, "Adaptive energy management strategy for optimal power flow control of hybrid DC microgrid," in *2020 5th International Conference on Smart and Sustainable Technologies (SpliTech)*, Sep. 2020, pp. 1-6.

[11] Z. Pu, L. Wan, M. Wu, and W. Wang, "Design of intelligent micro network group intelligent operation and maintenance management platform based on cloud architecture," in *2020 IEEE 3rd International Conference on Automation, Electronics and Electrical Engineering (AUTEEE)*, Nov. 2020, pp. 523-526.

[12] M. A. Rahman, M. R. Islam, K. M. Muttaqi, and D. Sutanto, "Data driven coordinated control of converters in a smart solid state transformer for reliable and automated distribution grids," *IEEE Transactions on Industry Applications,* vol. 56, no. 4, pp. 4532-4542, 2020.

[13] B. K. Ghosh, S. Sen, and S. Chanda, "Intelligent energy management systems for optimal techno-commercial benefit in DC micro-grids: A review," in *2020 IEEE VLSI Device Circuit and System (VLSI DCS)*, 2020, pp. 1-6.

[14] Using cyber-physical system-enabled microgrid system for optimal power utilization and supply strategy, by M. V. Ramesh, A. R. Devidas, and P. V. Rangan. (2021, Oct. 12). U.S. Patent 11,145,012 [Online]. Available: http://patft.uspto.gov/netacgi/6,885,550.

[15] S. Sahu, R. Dutt, and A. Acharyya, "Control strategy for efficient utilisation of regenerative power through optimal load distribution in hybrid energy storage system," in *2021 IEEE International Symposium on Circuits and Systems (ISCAS)*, May. 2021, pp. 1-5.

[16] M. Sharmila and R. V. S. Satyanarayana, "An intelligent resource allocation strategy for machine type communication environment," *International Journal of Communication Systems,* vol. 37, no. 1, p. e5628, 2024.

[17] V. Vanitha and E. Vallimurugan, "A hybrid approach for optimal energy management system of internet of things enabled residential buildings in smart grid," *International Journal of Energy Research,* vol. 46, no. 9, pp. 12530-12548, 2022.

[18] S. Walgama, S. Kumarawadu, and C.D. Chandima, "A stepwise approach based optimal energy utilization scheme for HVAC secondary chilled water pumps in commercial buildings," *International Energy Journal,* vol. 22, no. 4, pp. 389-400, 2022.

[19] H. Kim and J. Choi, "Intelligent access control design for security context awareness in smart grid," *Sustainability,* vol. 13, no. 8, p. 2124, 2021.

[20] C. Corchero and F. J. Heredia, "Optimal day-ahead bidding strategy in the MIBEL's multimarket energy production system," in *2010 7th International Conference on the European Energy Market*, Jun. 2010, pp. 1-6.

[21] Q. Yu, Y. Liu, Z. Jiang, and G.Long, "Design and accomplishment of AI control strategy with API in nearly zero energy building smart grid," in *2020 IEEE 6th International Conference on Control Science and Systems Engineering (ICCSSE)*, Jul. 2020, pp. 222-226.

[22] A. A. Alahmadi et al., "Hybrid wind/PV/battery energy management-based intelligent non-integer control for smart dc-microgrid of smart university," *IEEE Access*, vol. 9, pp. 98948-98961, 2001.

[23] G. Kannayeram, N. B. Prakash, and R. Muniraj, "Intelligent hybrid controller for power flow management of PV/battery/FC/SC system in smart grid applications," *International Journal of Hydrogen Energy,* vol. 45, no. 41, pp. 21779-21795, 2020.

[24] P. Annapandi, R. Banumathi, N. S. Pratheeba, and A. A. Manuela, "Power flow management scheme of hybrid renewable energy source to maximize power transfer capability using i2hosoa approach," *Journal of Intelligent & Fuzzy Systems*, vol. 39, no. 3, pp. 4159-4181, 2020.

[25] V. Gajula and R. Rajathy, "An explorative optimization algorithm for sparse scheduling in-home energy management with smart grid," *Circuit World,* vol. 46, no. 4, pp. 335-346, 2020.

[26] M. Azaroual, N. T. Mbungu, M.Ouassaid, M.W. Siti and M.Maaroufi, "Toward an intelligent community microgrid energy management system based on optimal control schemes," *International Journal of Energy Research,* vol. 46, no.15, pp. 21234-21256, 2022.

[27] J. Tong, T. Zhao, X. Yang, and J. Zhang, "Intelligent charging strategy for PHEVs in a parking station based on Multi-objective optimization in smart grid," in *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, Aug. 2014, pp. 1-6.

[28] V. Boglou, C. S. Karavas, A. Karlis, and K. Arvanitis, "An intelligent decentralized energy management strategy for the optimal electric vehicles' charging in low—Voltage islanded microgrids," *International Journal of Energy Research,* vol. 46, no. 3, pp. 2988-3016, 2022.