NARI 国电南瑞科技股份有限公司
NARI TECHNOLOGY CO.,LTD.

分布式光伏与梯级小水电互补联合发电技术研究及应用示范
Technology Research and Application Demonstration for Complementary Combined Power Generation of Distributed PV and Cascaded Small Hydropower


南京南瑞水利水电科技有限公司
NANJING NARI WATER RESOURCES AND HYDROPOWER TECHNOLOGY COMPANY LIMITED

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技术背景
Technical Background

新能源大规模并网对电力系统的挑战The Challenges of Integrating Increasing Amounts of new energy to Power System

1、新能源大规模并网给电力系统的稳定运行带来挑战
The challenges of integrating increasing amounts of new energy brought to stable operation of the power system

新能源大规模并网影响电力系统发输配用全部电力环节，然而受风电和光伏自身出力的随机性、间歇性以及不稳定性的资源特性影响，突出表现为对新能源的预测难、控制难、调度难。

2、我国电力系统灵活性调节电源严重缺乏
China's power system seriously lack of flexible regulating power sources

新能源的发电随机波动，发电功率预测误差较大，高比例新能源接入电力系统后，支撑电源不仅要跟随负荷变化，还要跟踪平衡新能源的出力波动，增加了电力系统调节负担，致使新能源协调发电计划安排和优化调度运行难度大。

3、多能互补技术是新能源发电由随机到可控的有效途径
Multi-energy complementary technology is an effective way for new energy generation from random to controllable.

据预测，2050年可再生能源占中国一次能源消费的比重应超过50%，可再生能源电力占电力消费的比重将超过70%，高比例的可再生能源已是中国能源发展的必然趋势，高比例新能源并网需要有效的应对措施，多能互补技术是新能源高比例并网由随机到可控的有效途径。

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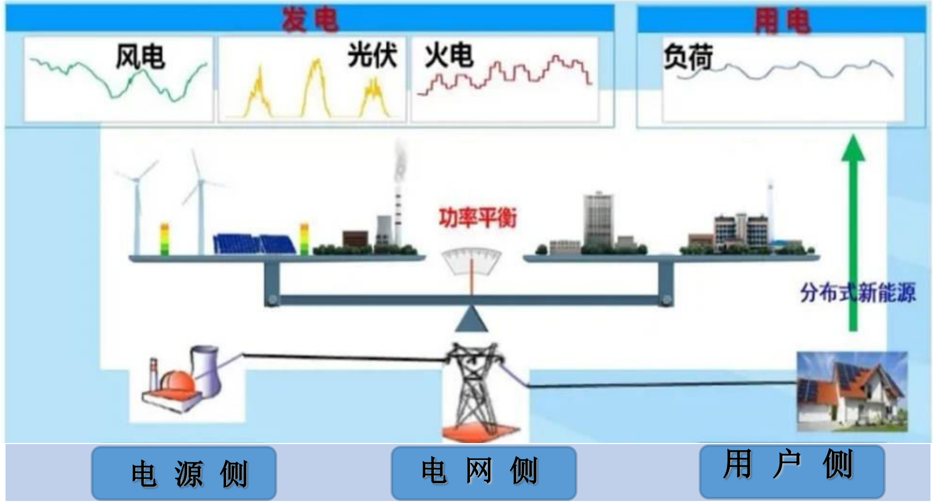
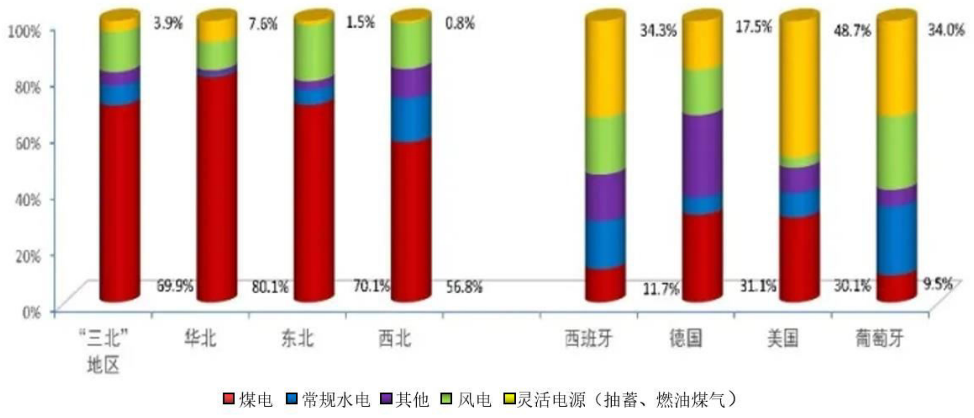


新能源功率随机性给电力系统运行带来挑战
RES power randomness brings challenges to the operation of power system.



国内外灵活性调节电源情况对比
Comparison of domestic and foreign flexible regulating power supply

新能源的发电特性
New Energy Power Generation Characteristics

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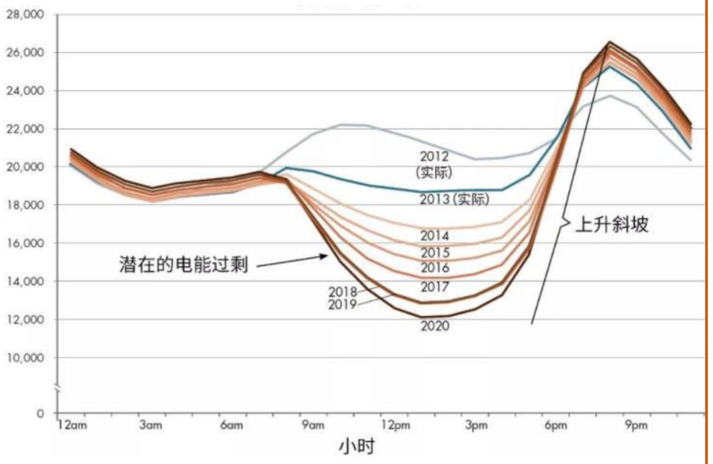
风功率特性Wind power characteristics：风电在多日内的规律性较差，但一般其在几小时甚至几十各小时内的持续性较好，因此可以基于风功率预测进行火电机组启停调整。

光伏功率特性PV power characteristics：光伏在多日内的规律性较强，但每天都要经历从零到接近满出力再到零的过程，在当前缺少低成本快速启停电源的条件下，解决大量光伏并网带来的中午低谷和午后负荷高峰交替的问题（就是常说的鸭型曲线），还是比较困难的。



但相较于火电、水电等传统能源，风光输出功率的不可控性确实为新能源的消纳带来很大问题。同时由于风电和光伏基本没有主动支撑的能力，大规模并网直接影响到电网的安全稳定运行。

水电、抽水蓄能由于其灵活、快速的特性，是解决以上问题的重要途径。
Hydropower and pumped storage are important for solving the above problems for their flexible and fast response characteristics.

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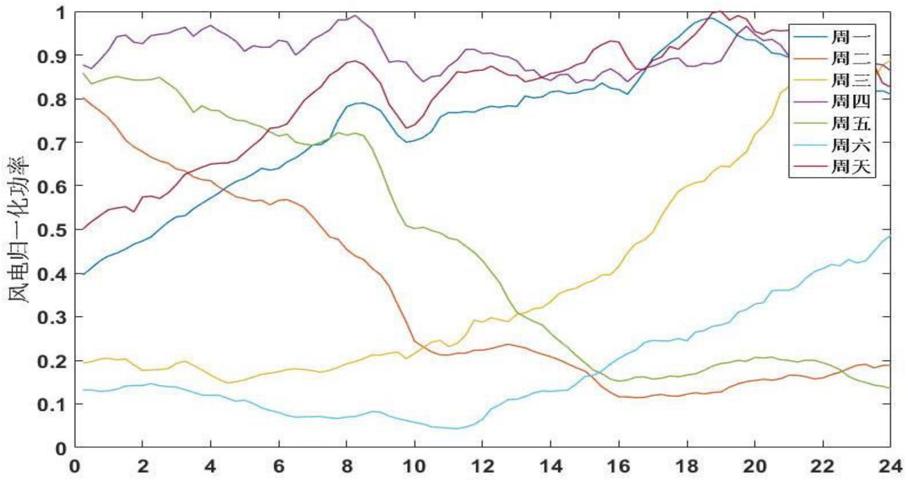
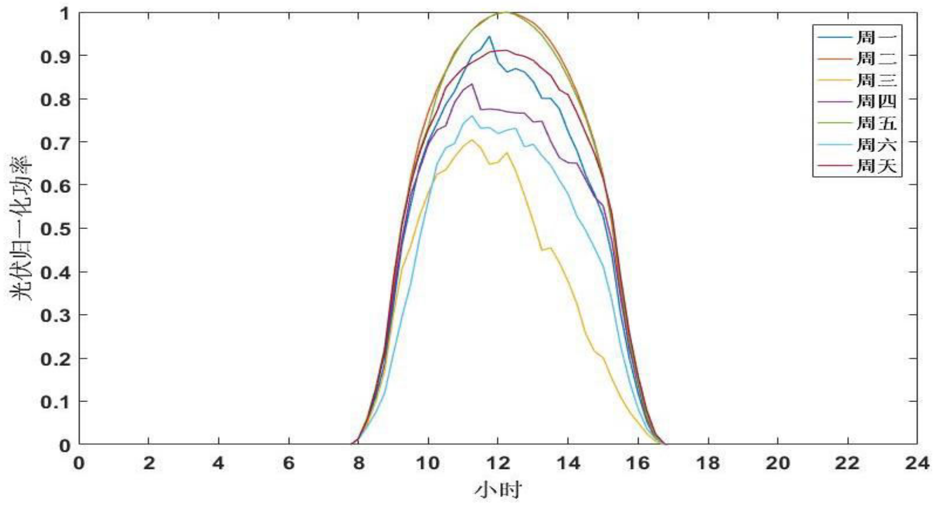


风电典型周功率曲线
Typical weekly power curve for wind power



光伏典型周功率曲线
Typical weekly power curve for PV power

项目概况
PROJECT OVERVIEW

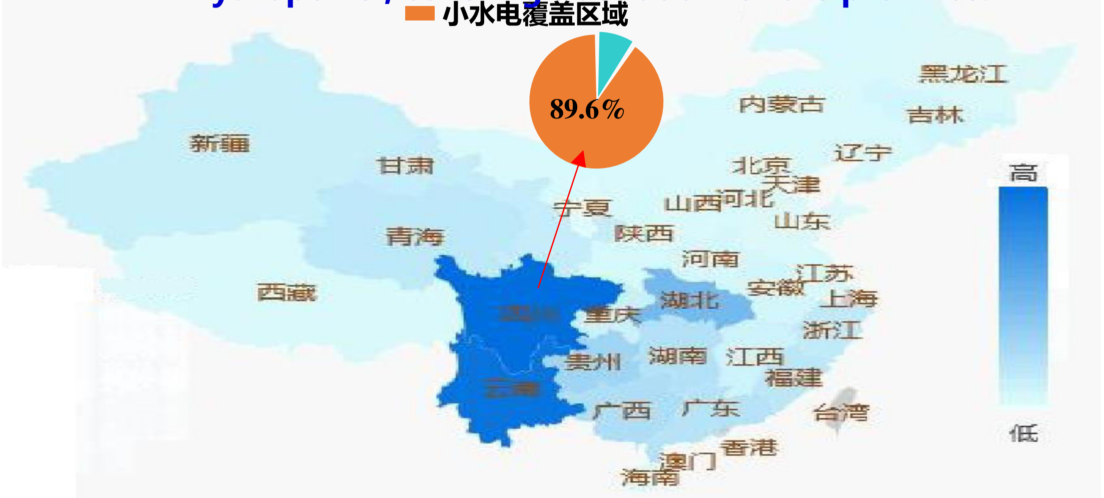
“全面推进分布式光伏发电建设，推动多能互补、协同优化的新能源电力综合开发 “ 是《电力发展“十三五”规划》[1] 的重点任务之一 。"

- **我国水电装机世界第一，其中小水电约占23.5%**
  China's installed hydropower capacity ranks first in the world.
- **水电集中于西南地区，水能和太阳能资源丰富**
  Hydro and pv power is concentrated in the southwest region.
- **梯级电站形成天然的抽水蓄能上下库**
  Cascaded hydropower plants form natural pumped storage reservoirs.

具备发展水、光、蓄互补联合发电的优越条件

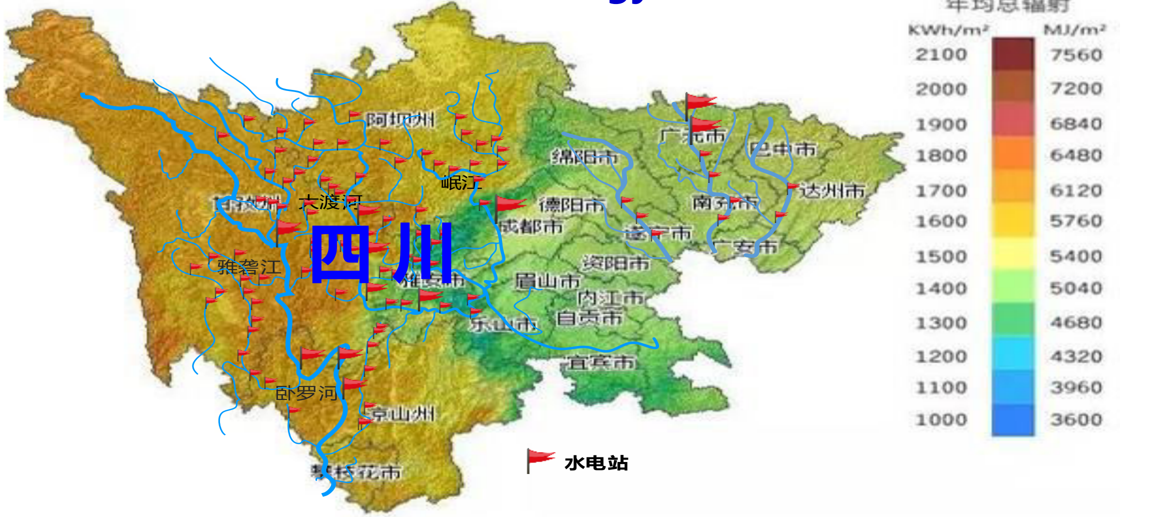
Favorable conditions for the development of complementary combined power generation of hydropower, solar and storage.

四川小水电装机全国第一，遍布全省约90%区域
Sichuan ranks first in China in terms of installed capacity of small hydropower, covering about 90% of the province.



2020年全国水电装机分布情况
Distribution of Installed Hydropower Capacity Nationwide in 2020

流域范围内太阳能资源丰富
There are abundant solar energy resources in the river basins.



四川省太阳能资源分布情况
Distribution of solar energy resources in Sichuan Province

2 存在问题Pending Problems

并网运行 On-grid operation → 灾害、故障、检修 Disaster, Fault, Overhaul → 离网运行 On-grid operation

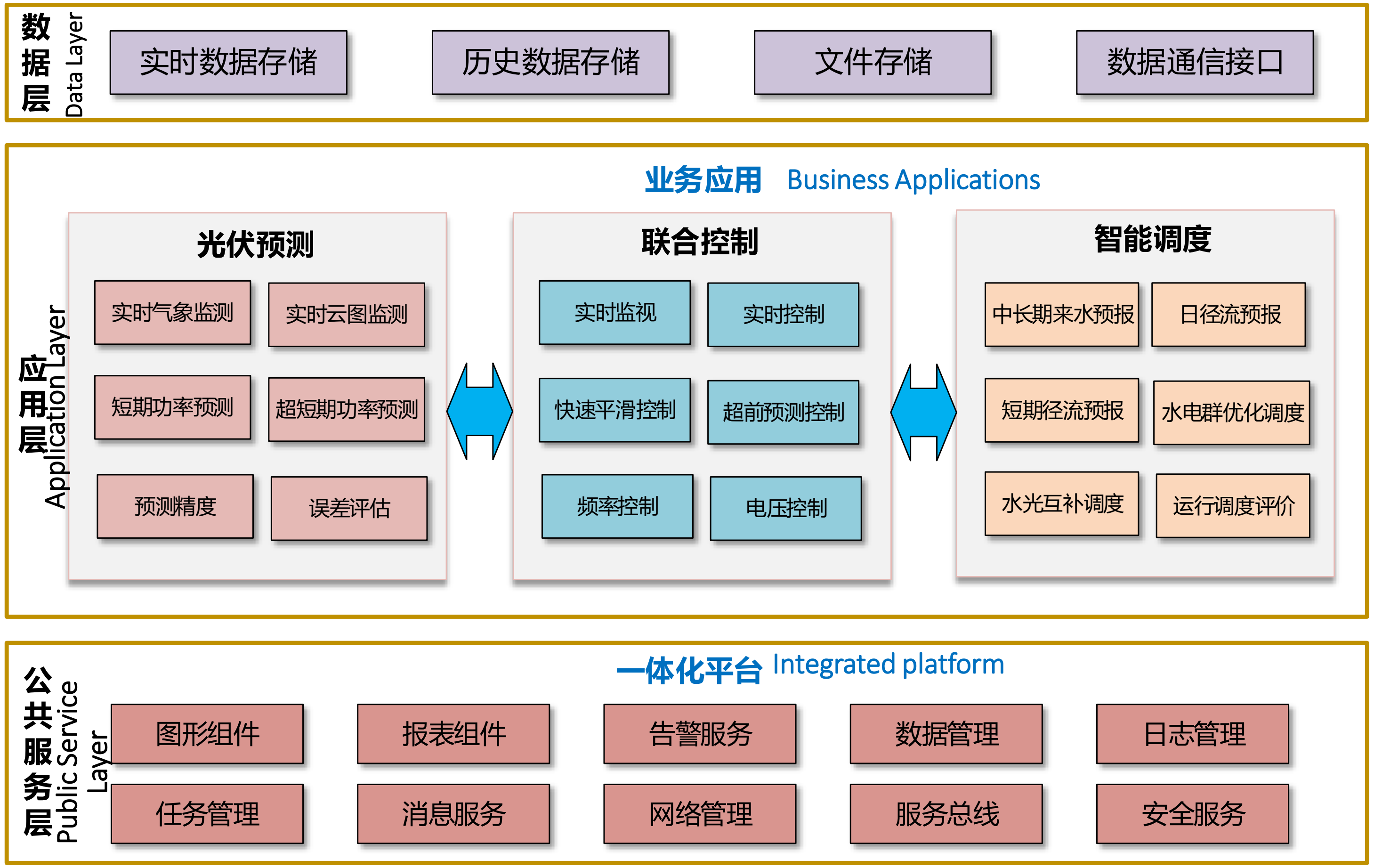
	并网运行 On-grid operation	离网运行 On-grid operation
稳态 Steady state	小水电库容小 调节能力弱	电力电量平衡困难 清洁能源利用率低 弃光、弃水、拉闸限电并存
暂态 Transient state	小水电长距离接入主网 暂稳/动稳受限 窝电严重	调频调压困难 垮网风险高

高占比新能源发电随机出力波动大幅增加并网和离网运行的难度
Random fluctuation of high scale of RES significantly increase the difficulty of on-grid and off-grid operation

3 系统功能System Functions

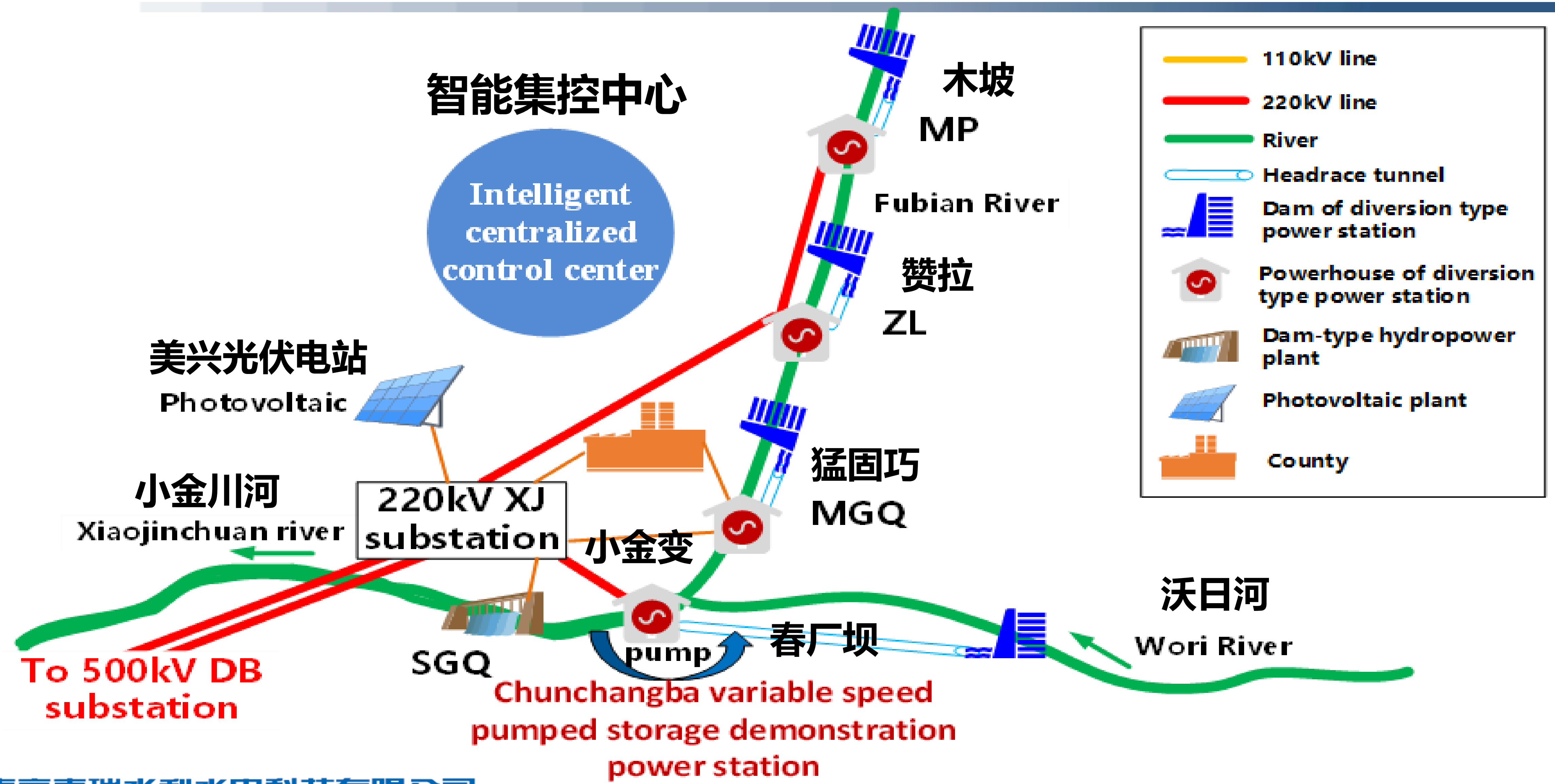
梯级水光蓄联合运行控制与智能调度系统对区域内梯级水电、光伏和抽蓄等电源进行统一的数据采集处理，实现运行监视与分析，功率预测、发电能力分析、联合发电计划制定、消纳分析等决策支持和实时运行控制等功能，通过水电站和抽水蓄能电站的调节能力，平抑光伏发电的随机性和波动性，提高清洁能源的利用水平，提升电网对新能源的接纳能力。

The complementary combined power generation system provides unified data acquisition and processing to the power sources such as cascaded hydropower, PV and pumped storage, and offers decision support for operation monitoring and analysis, power prediction, power generation capacity analysis, development of combined power generation schedules and the functions of real-time operation control. With the regulation capacity of hydropower and pumped storage, it will smooth out the randomness and fluctuation of PV power, improve the utilization level of clean energy, and enhance the absorptive capacity of the grid for new energy.



系统功能框图

System Function Block Diagram



小金川流域示范工程示意图
Schematic diagram of the demonstration project

联合运行控制技术
Combined Operation Control Technology

1 运行方式Operation Mode

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■ 梯级水光蓄采用主从运行，多级调节的运行方式。

The combined operation control system adopts the operation mode of master-slave operation and multi-stage regulation.

■ 主从是梯级水电为主，变速抽蓄为辅，共同实现对光伏出力平滑控制。

Master-slave operation is dominated by cascaded hydropower and supplemented with variable speed pumped storage, to offset the fluctuation of PV output.

■ 多级调节是指通过梯级水电、变速抽蓄等多个调节电源进行功率调节。

Multi-stage regulation refers to the power regulation through multiple regulating power sources including cascaded hydropower and variable speed pumped storage.

主从运行 Master-slave operation	多级调节 Multi-stage regulation	
梯级水光蓄并列组网运行 梯级水电为主，支撑区域电网 变速抽蓄为从，平抑光伏快速波动	梯级水电	主要调节电源，光伏分钟级波动优先调节电源
	抽蓄	光伏秒级波动优先调节电源
	光伏	非必要出力不受限制

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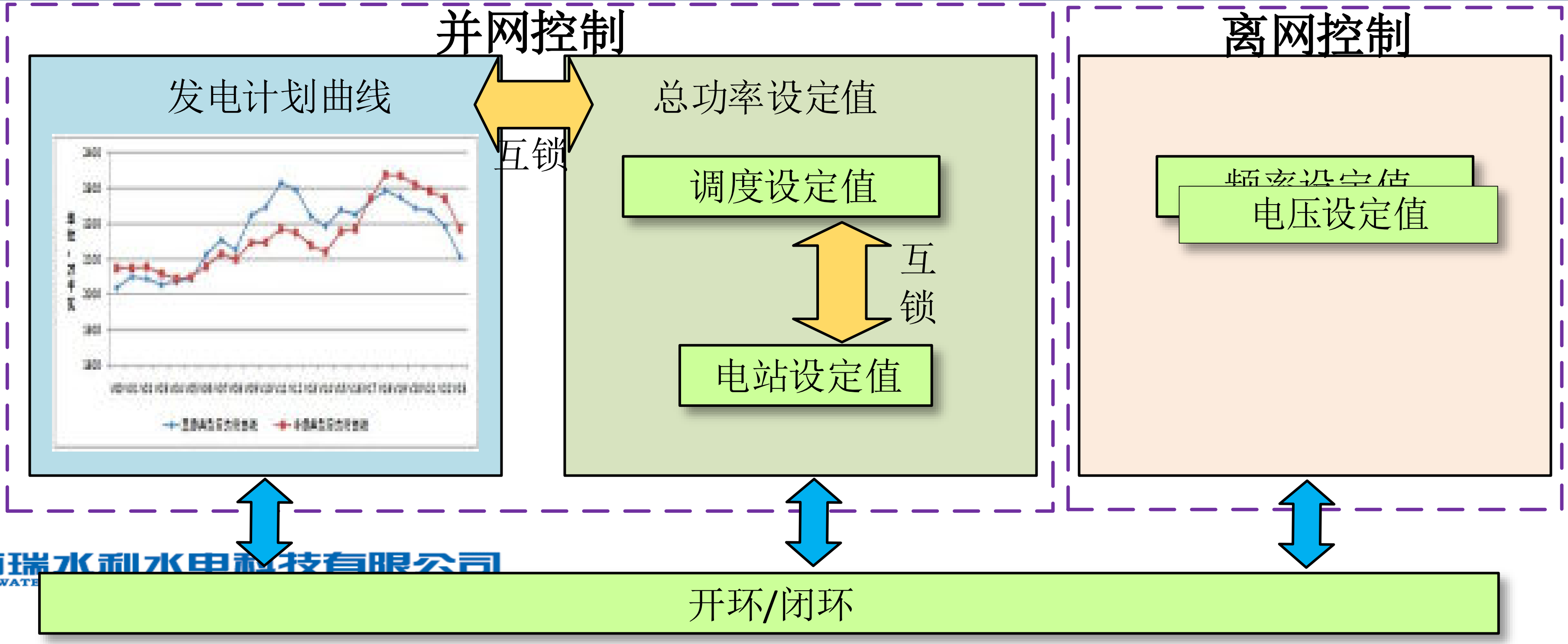
梯级水光蓄联合运行控制包括并网控制和离网控制两种模式。

The combined operation control of cascaded hydro-solar-pumped storage includes two modes: on-grid control and off-grid control.

- 并网控制时，系统可根据调度发电计划曲线或总功率设定值对联合出力进行调节。
  On-grid control mode: the system can regulate the combined output according to the dispatching generation schedule curve or the total power setting value.
- 离网控制时，系统维持示范区频率和电压稳定在允许范围。
  Off-grid control mode: the system maintains the frequency and voltage stability of the demonstration zone within the allowable range.



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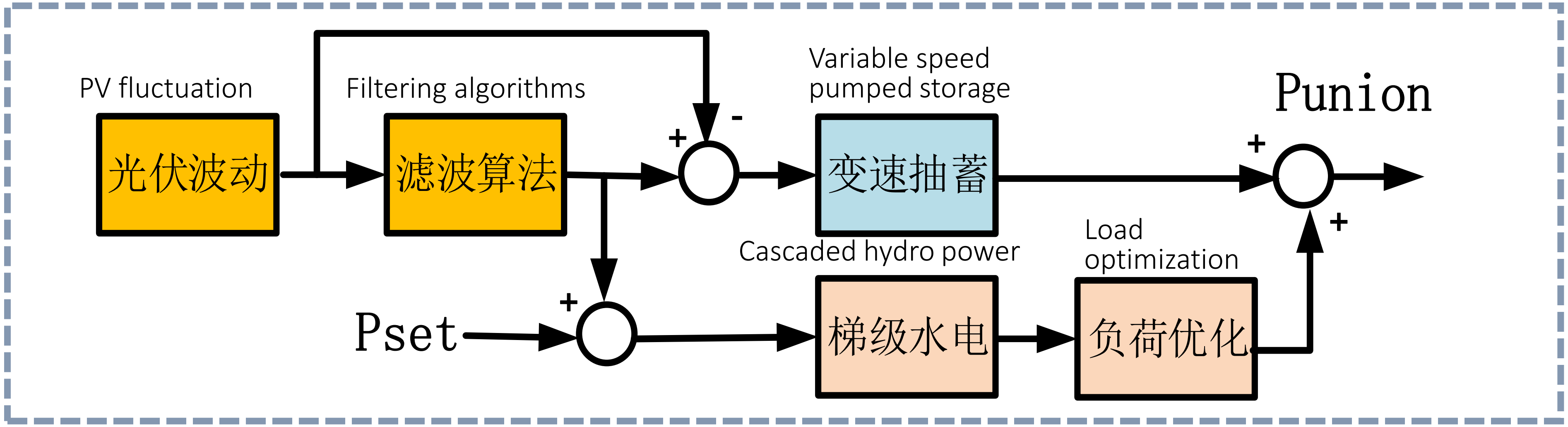
梯级水光蓄联合运行控制模型基于梯级水电实时负荷优化控制方法，并使用光伏滤波算法分离光伏波动功率的高、低频分量；通过梯级水电平抑光伏分钟级低频波动分量，变速抽蓄平抑光伏秒级高频波动分量，实现对光伏出力波动的平滑控制。

The model of combined operation control system is based on the cascaded hydropower real-time load optimization control method, and uses PV filtering algorithm to separate the high and low frequency components of PV fluctuation. It helps offset the PV fluctuation through the cascaded hydropower leveling the low frequency of fluctuating components at the minute timescales, and the variable speed pumped storage leveling the high frequency of fluctuating components at the second timescale.



梯级水光蓄控制模型示意图

Diagram of the Cascaded Hydro-PV-Storage Control Model

4 预测控制模型Predictive Control Model

基于高精度光伏预测数据，构建梯级水电与光伏的预测控制模型，利用每5分钟的滚动优化计算下一时刻（5/15min）梯级各水电站计划出力和开停机组合，并考虑机组爬坡率等因素完成机组的自动开停机和负荷优化分配，通过对历史出力偏差对机组实时出力进行反馈矫正，实现对水光联合出力的精准调控。

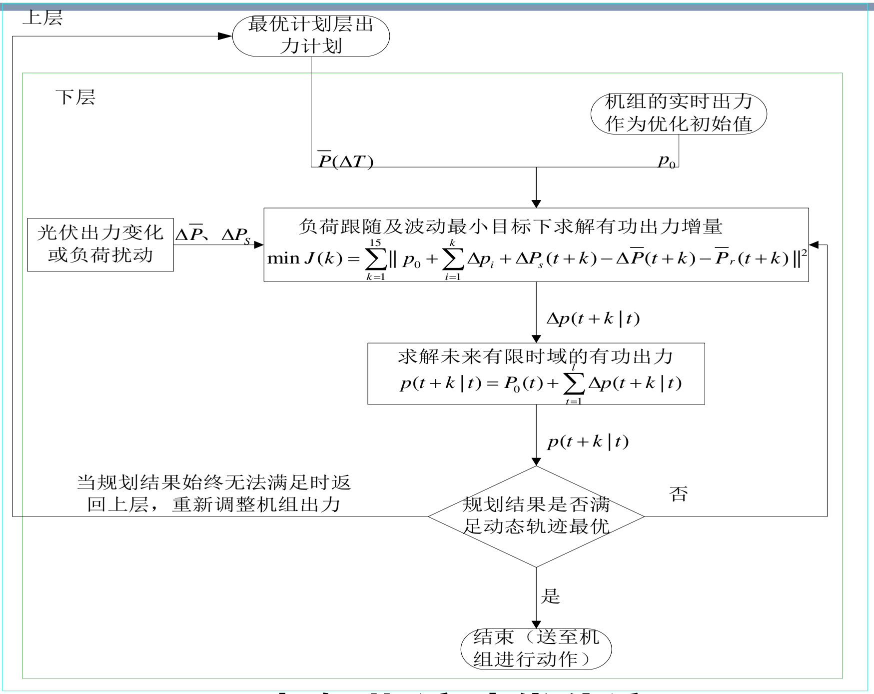
The predictive control model is built based on high-precision PV prediction, which calculate the scheduled output and unit commitment of cascaded hydropower plants for the next time interval (5/15 minutes) by rolling optimization every 5 minutes. It completes the automatic startup/shutdown and optimal load assignment of units by considering the ramping rate of units, and makes feedback and correction of real-time units output using the historical output deviation, so as to realize the accurate regulation of the combined operation control system .

梯级水光预测控制模型

Predictive Control Model of combined operation control system

$$p(k+j|k)=\overline{P}(k+j|k)+f_j(p(k)-\overline{P}(k|k))$$

$$f_j=\begin{cases}1 & j=1\\ a & j=2...N-1\end{cases}$$



超短期滚动优化流程图

Ultra-Short-Term Rolling Optimization Flow Chart

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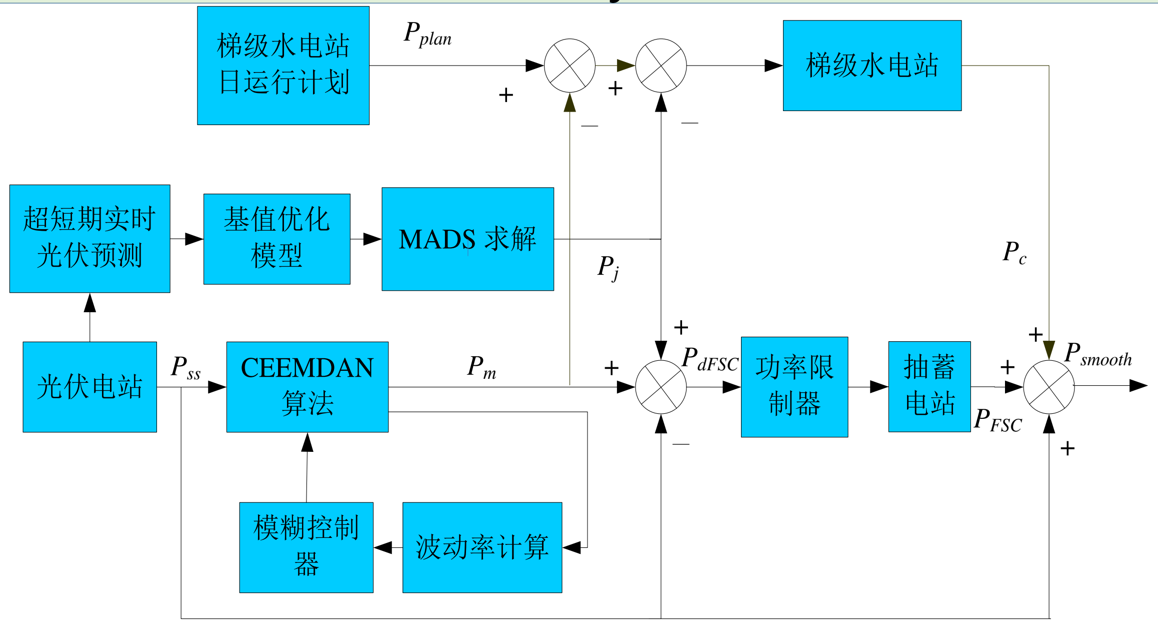
（1）层次化控制策略 Hierarchical control strategy

对梯级水电机组、抽水蓄能机组及光伏电站采用层次化控制策略，即对不同的电源根据其调节性能使用不同的调控方法，并使联合调控达到快速、平稳的控制目标。
The hierarchical control strategy is applied to the cascaded hydropower units, pumped storage units and PV power plants, different regulation and control methods are applied for different power sources according to their regulation performance, making the combined regulation and control achieve fast and smooth control objectives.



层次化控制框图
Hierarchical Control Block Diagram

利用抽水蓄能机组快速响应能力，抑制光伏出力突变波动，变速抽蓄数学模型如式：
Using the rapid response ability of pumped storage units to suppress abrupt fluctuation in PV output, the mathematical model of variable speed pumped storage is as the Equation:

$$P_{dFSC} = P_m - P_{ss} + P_j$$

结合梯级水光蓄互补电站滚动发电计划，利用梯级水电站平滑光伏电站趋势性波动，梯级水电站数学模型如式：
Combined with the rolling power generation schedule of the cascaded hydro-PV-storage complementary power plants and using the cascaded hydropower plants to smooth out the trend fluctuations of the PV power plants, the mathematical model of the cascaded hydropower plant is as Equation:

$$P_c = P_{plan} - P_m - P_j$$

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（2） 梯级水位控制策略 Cascaded water level control strategy

在梯级水电实时负荷控制过程中，首先要确保大坝的运行安全。一方面水库水位过高影响大坝和下游的生产安全，并产生弃水；另一方面，水库水位过低将拉空水库，不利于机电设备的安全运行。因此在梯级水电联合运行中采用水位控制模型，该模型以各级电站水库水位变化最小为控制目标，按流量平衡进行厂间负荷分配，实现负荷与流量上的匹配，达到各级水库水位尽可能平稳的目的。

In the process of real-time load control of the cascaded hydropower, it is necessary to ensure the operational safety of dam in the first place. On one hand, too high reservoir level will affect the production safety of the dam and the downstream, resulting in water abandonment; on the other hand, too low reservoir level will discharge the reservoir empty, which is not conducive to the safe operation of mechanical and electrical equipment. Therefore, the water level control model is used in the combined operation of the cascaded hydropower. This model takes the minimum change of water level of reservoirs as the control objective, and carries out load assignment between plants according to the flow balance to achieve the matching of load and flow, so as to achieve stable water level of reservoirs as much as possible.

水位平稳模型

Stable water level model

$$F=\min\left(\left|Z_{s,t+\tau}-Z_{s,t}\right|+A+\left|Z_{z,t+\tau}-Z_{z,t}\right|+B\right)$$

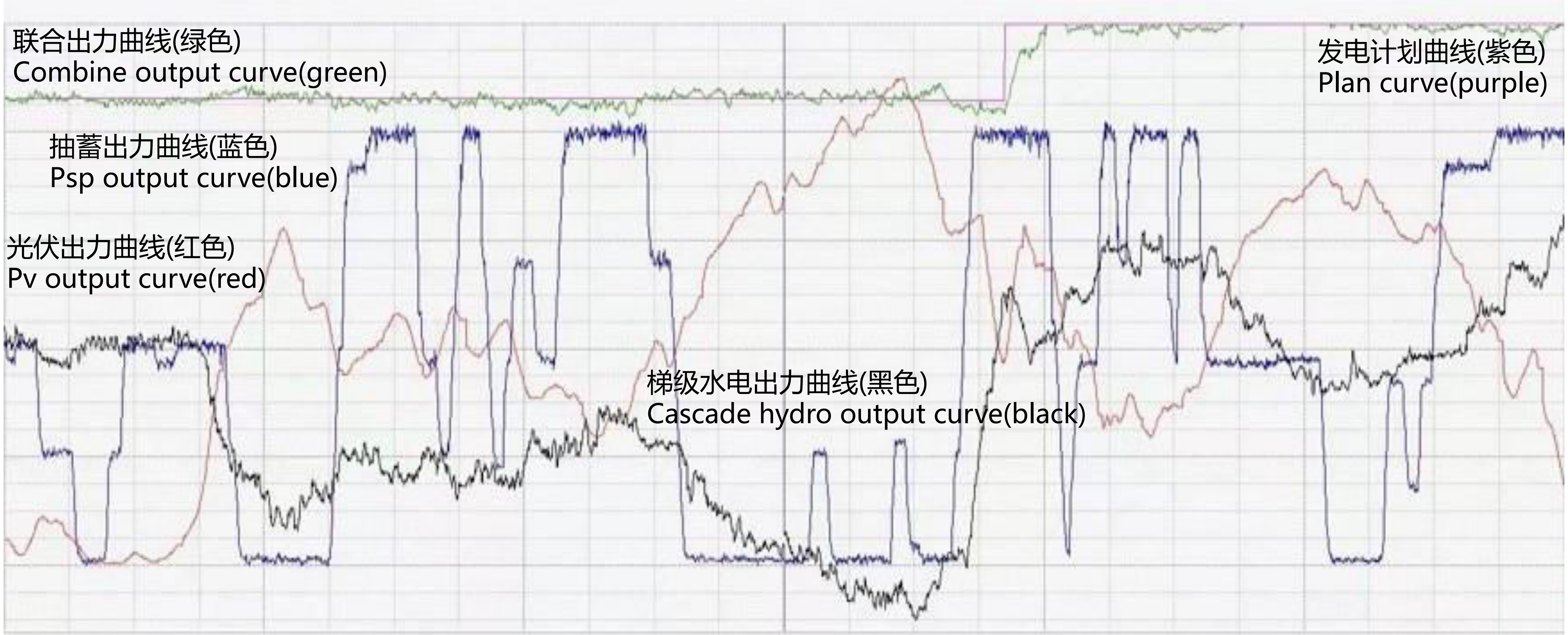
水位异常控制模型

Water level abnormality control model

$$F=\min\left(\alpha\left|Z_{s,t+\tau}-\frac{Z_{s,down}+Z_{s,up}}{2}\right|+\beta\left|Z_{z,t+\tau}-\frac{Z_{z,down}+Z_{z,up}}{2}\right|\right)$$

这是梯级水光蓄互补发电动态试验的曲线图。

This is the graph of the dynamic test of cascade hydro-solar pumped storage hybrid power generation, and we will explain the test results one by one.

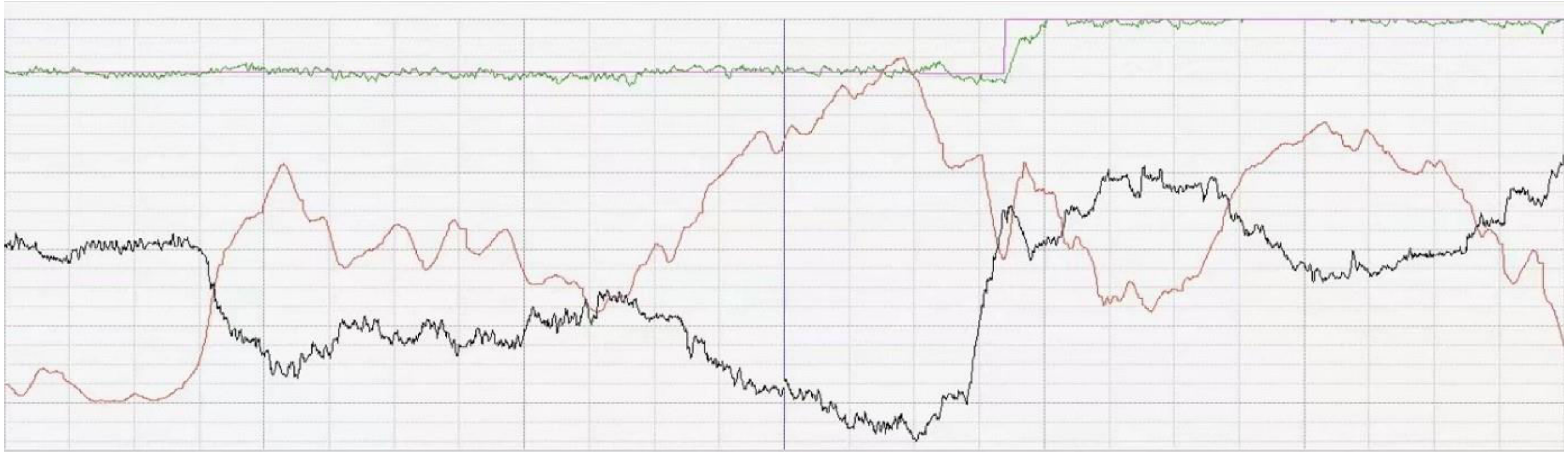


下图展示了变速抽蓄机组与光伏的快速平滑控制曲线，变速抽蓄可快速响应光伏出力的突变，并在可调出力范围内实现光伏的秒级出力平滑。

The figure below shows the fast smooth-control curve of the variable speed pumped storage unit and PV. The variable speed pumped storage is capable of providing quick response to the sudden change of PV output and smooth out the PV output fluctuation at the seconds timescale within the adjustable output range.

下图展示了水电与光伏的互补控制曲线，水电机组可在变速抽蓄机组调节的基础上，实现对光伏出力的分钟级平滑控制，通过水电+变速抽蓄的联合互补，实现对光伏出力高低频波动分量的快速平抑。

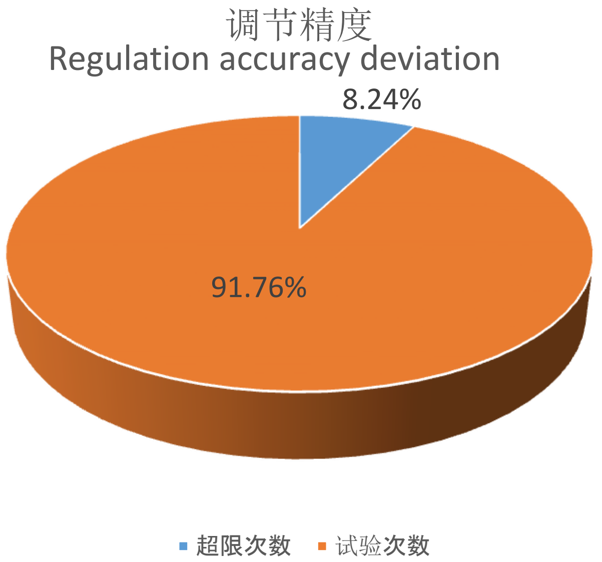
The figure below shows the complementary curve of hydropower and PV. The hydropower unit can realize smooth-control of PV at the minute timescale, and the system can rapidly level out the high and low frequency fluctuation components of PV through the combined complementary of hydropower and variable speed pumped storage.

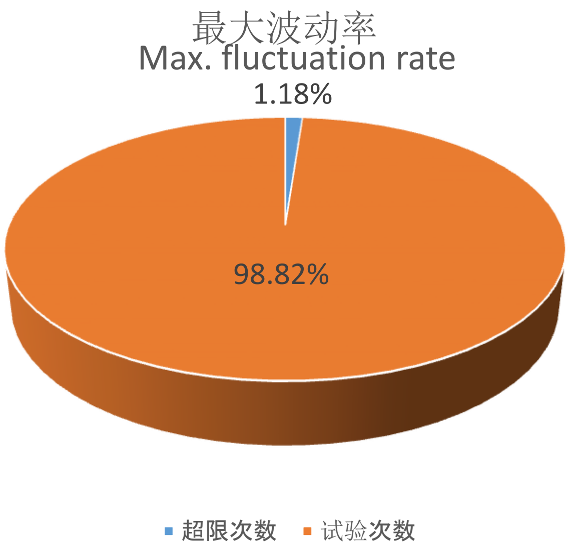


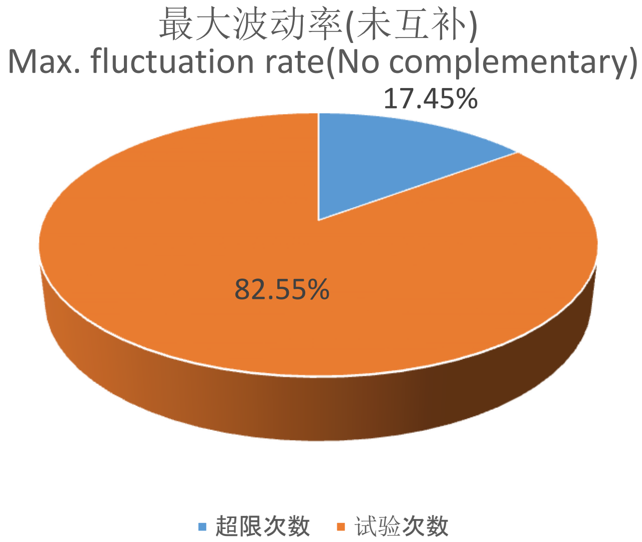
7梯级水光蓄互补指标分析
Analysis on cascaded hydro-solar-pumped storage complementary Indicators

下图展示了试验过程中指标样本的统计情况，二次调频指令测试实时调节精度279次，23次超过3%，合格率为91.76%；实时平滑光伏测试最大波动率指标 6346次，75次超过8%，合格率为98.82%。同时，未进行平滑互补的波动测试共854次，其中148次超过最大波动率8%,合格率为82.55%。

The figure below shows the statistics of the indicator samples during the test:The real-time regulation accuracy deviation in the secondary frequency modulation command test is 279 times, 23 times of which exceeded 3%, with a pass rate of 91.76%; the maximum fluctuation rate indicator in real-time smooth-out PV test is 6346 times, 75 times of which exceeded 8%, with a pass rate of 98.82%. While the fluctuation test without smooth-out complementary shows a total of 854 times, 148 of which exceeded the maximum fluctuation rate of 8%, with the pass rate as low as 82.55%.



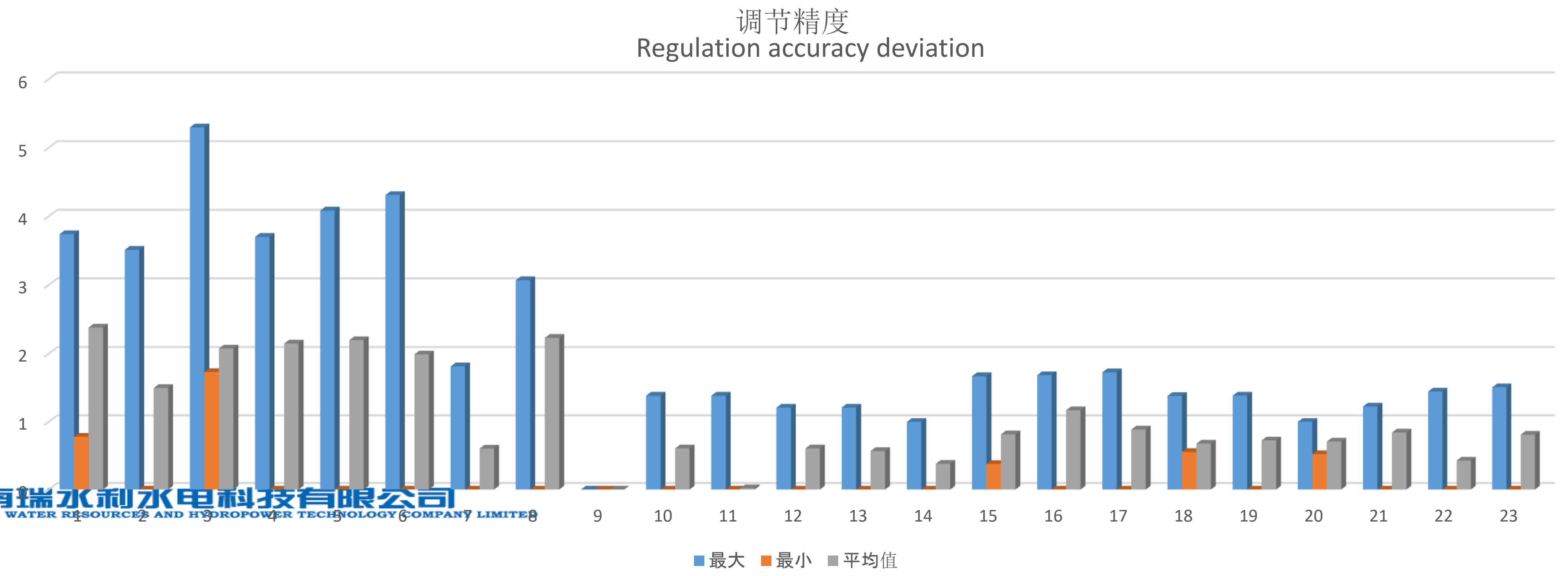




7梯级水光蓄互补指标分析
Analysis on cascaded hydro-solar-pumped storage complementary Indicators

下图展示了实时调节精度偏差的指标统计图，实时调节精度在枯水期机组可用出力较少时不能完全对光伏出力波动进行互补，导致指标偏差最大为5.296%；进入平水期和丰水期后，机组可用出力可实现对光伏出力波动的互补，实时调节精度可控制在1.5%以内。

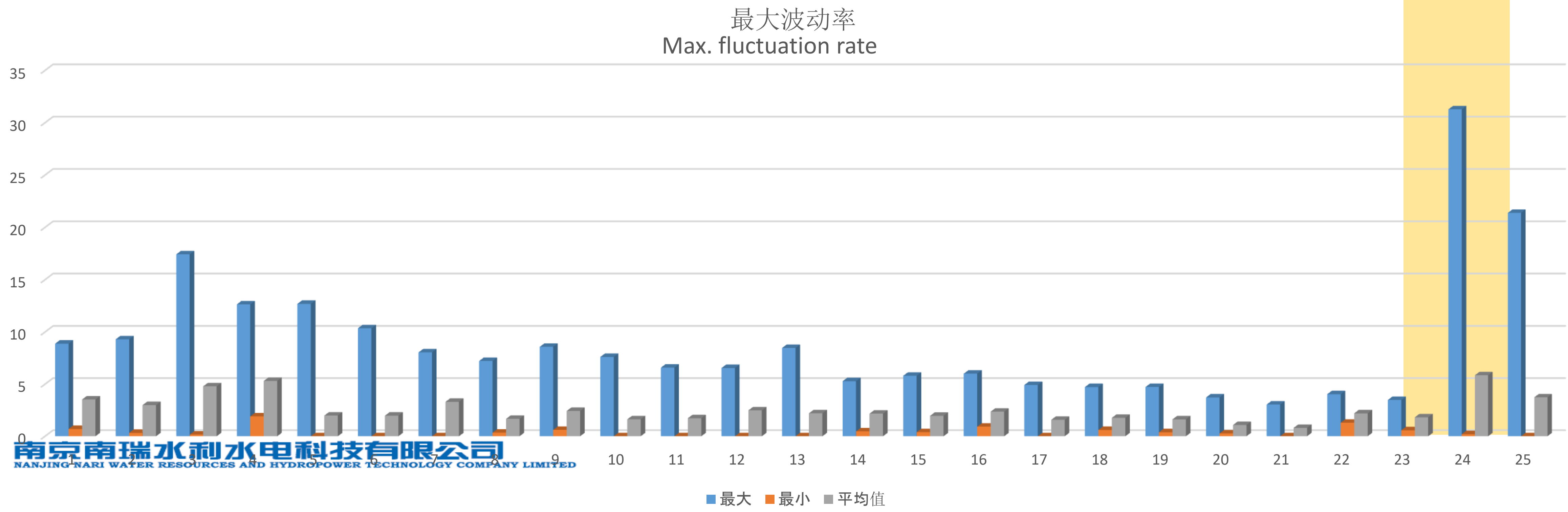
The figure below shows the statistics of the indicator samples during the test:The real-time regulation accuracy deviation in the secondary frequency modulation command test is 279 times, 23 times of which exceeded 3%, with a pass rate of 91.76%; the maximum fluctuation rate indicator in real-time smooth-out PV test is 6346 times, 75 times of which exceeded 8%, with a pass rate of 98.82%. While the fluctuation test without smooth-out complementary shows a total of 854 times, 148 of which exceeded the maximum fluctuation rate of 8%, with the pass rate as low as 82.55%.



7梯级水光蓄互补指标分析
Analysis on cascaded hydro-solar-pumped storage complementary Indicators

下图展示了最大功率波动率的实时统计图，最大波动率在枯水期机组可用出力较少时不能完全对光伏出力波动进行互补，导致指标偏差最大为17.421%；进入平水期和丰水期后，机组可用出力可实现对光伏出力波动的互补，最大波动率可控制在5%以内。

The figure below shows the real-time statistics of the maximum fluctuation rate. The maximum fluctuation rate cannot fully offset the fluctuation of PV output when the available output of the units is small during the dry season, resulting in a maximum indicator deviation of 17.421%. After entering the flat season and wet season, the available output of the units can offset the fluctuation of PV output, and the maximum fluctuation rate can be controlled within 5%. In each regulation process, the average value of the maximum fluctuation rate meets the requirements of the project.



南京南瑞水利水电科技有限公司
NANJING NARI WATER RESOURCES AND HYDROPOWER TECHNOLOGY COMPANY LIMITED

智能调度技术
Intelligent Dispatching Technology

NARI 国电南瑞科技股份有限公司 NARI TECHNOLOGY CO.,LTD.

根据反映互补发电系统总出力与电网负荷需求匹配程度的**源荷匹配系数**，提出以**源荷匹配最佳**、**总出力波动最小**、**总发电量最大**为目标函数构建梯级水光蓄互补电站联合调度模型。
Based on the **source-load matching coefficient**, which reflects the degree of matching between the total output of the complementary power generation system and the load demand of the power grid, the combined dispatching model of the complementary power plant is proposed to be constructed with the objective function for **the optimalbest source-load matching, the minimum fluctuation of the total output and the maximum total power generation**.

◆ 源-荷匹配系数
Source-load matching coefficient

$$M=\sqrt{\sum_{t=1}^{T}\left(N_t-N_{f,t}\right)^2}$$

$$\begin{cases} N_t=\sum_{i=1}^{n}N_{h,i,t}+N_{T,t}-N_{P,t}+N_{pv,t} \\ N_{h,i,t}=K_i\cdot Q_{i,t}\cdot H_{i,t} \\ N_{T,t}=g\cdot\eta_T\cdot Q_{T,t}\cdot H_{T,t} \\ N_{P,t}=\dfrac{g\cdot Q_{P,t}\cdot H_{P,t}}{\eta_P} \end{cases}$$

$$H_{i,t}=\frac{Z_{i,t\text{-}1}+Z_{i,t}}{2}-Zd_{i,t}-HLoss_{i,t}$$

$$H_{T,t}=\frac{Zs_{t\text{-}1}+Zs_t}{2}-\frac{Zd_{t\text{-}1}+Zd_t}{2}-HLoss_{T,t}$$

$$H_{P,t}=\frac{Zs_{t\text{-}1}+Zs_t}{2}-\frac{Zd_{t\text{-}1}+Zd_t}{2}-HLoss_{P,t}$$

目标函数 Objective function

1 以源-荷匹配为目标
Aim for source-load matching

$$\min M=\sqrt{\sum_{t=1}^{T}\left(\sum_{i=1}^{n}N_{s,t,i}+N_{p,t}-N_{h,t}\right)^2}$$

2 以总出力波动最小为目标
Aim for the minimum fluctuation of total output

$$\min D_v=\sqrt{\frac{1}{T-1}\sum_{i=1}^{T}\left(N_{r,t}-\bar{N}_r\right)^2}$$

3 以总发电量最大为目标
Aim for the maximum total power generation

$$\max E=\sum_{t=1}^{T}\left(\sum_{i=1}^{n}N_{s,t,i}+N_{p,t}\right)M_t$$

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2 约束条件Constraint Conditions

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梯级小水电的约束条件
Constraints on cascaded small hydropower plants

- 水量平衡约束 Water balance constraint

$$\begin{cases} V_{i,t+1} = V_{i,t} + (R_{i,t} - Q_{ri,t})\Delta t \\ Q_{ri,t} = Q_{i,t} + S_{i,t} \end{cases}$$

- 水库水位约束 Reservoir water level constraint

$$Z_{i,t}^{\min} \le Z_{i,t} \le Z_{i,t}^{\max}$$

- 下泄流量约束 Discharged flow constraints

$$Q_{ri,t}^{\min} \le Q_{ri,t} \le Q_{ri,t}^{\max}$$

- 流量联系约束 Flow Connection Constraints

$$R_{i,t} = Q_{ri-1,t-\Delta T_{i-1}} + I_{i,t}$$

- 电站出力约束 Station output constraints

$$N_{h,i,t}^{\min} \le N_{h,i,t} \le N_{h,i,t}^{\max}$$

- 水电站振动区约束

Hydro vibration zone constraints

$$\left[N_{h,i,t} - \overline{NS}_{i,t,k}\left(Z_{i,t}, Z_{i,t+1}, Zd_{i,t}\right)\right]\left[N_{h,i,t} - \underline{NS}_{i,t,k}\left(Z_{i,t}, Z_{i,t+1}, Zd_{i,t}\right)\right] \ge 0$$

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分布式光伏电站的约束条件
Constraints on Distributed PV Power Plants

- 电站出力约束Power station output constraint

$$N_{pv,t}^{\min} \le N_{pv,t} \le N_{pv,t}^{\max}$$

抽蓄机组的约束条件
Constraints on pumped storage units

- 水量平衡约束Water balance constraint

$$V_{T,t+1} = V_{T,t} + (R_{T,t} - Q_{T,t} + Q_{P,t} - S_{T,t})\Delta t$$

- 上水库和下水库水位约束reservoir water level constraints

$$Zs_t^{\min} \le Zs_t \le Zs_t^{\max}$$

$$Zd_t^{\min} \le Zd_t \le Zd_t^{\max}$$

- 电站出力约束station output constraint

$$N_{T,t}^{\min} \le N_{T,t} \le N_{T,t}^{\max} \qquad N_{P,t}^{\min} \le N_{P,t} \le N_{P,t}^{\max}$$

3 算法求解Solve for Algorithm

在传统PSO算法的基础上，引入**动态调整学习因子**进行寻优过程的有效控制，**克服早熟收敛现象**，有效判别全局最优解。
Based on the traditional particle swarm optimization(PSO) algorithm, the dynamic adjustment learning factor is introduced for effective control of the optimization process and for overcoming the premature convergence phenomenon, thus effectively identifying the global optimal solution.

动态调整学习因子表达式
Expression of dynamic adjustment learning factor

- 动态调整学习因子
Dynamic adjustment learning factor

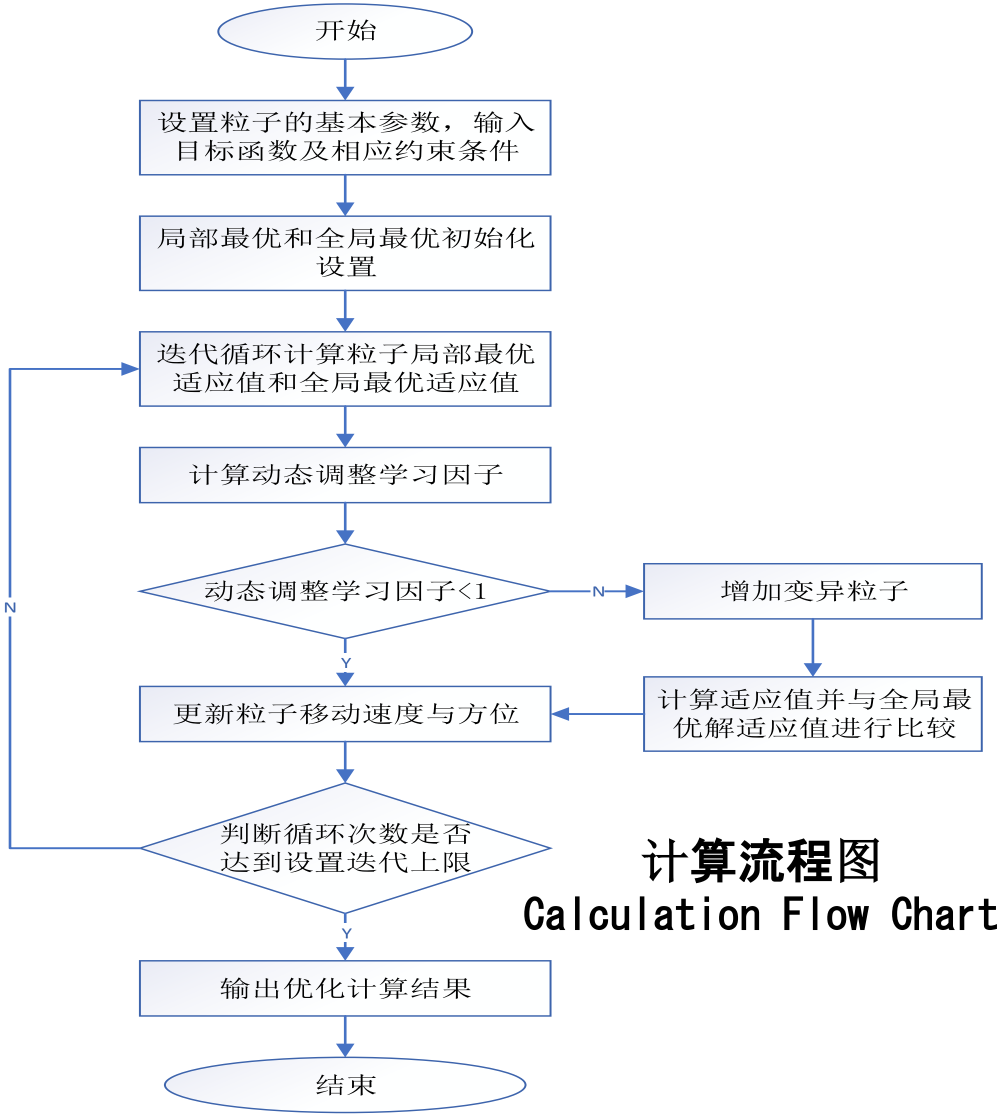
$$\sigma^2 = \sum_{i=1}^{m} \left(\frac{F\left(x_i^k\right) - F_{av}^k}{f^k} \right)^2$$

- 粒子群体平均适应值
Average adaptive value of particle population

$$F_{av}^k = \frac{1}{m} \sum_{i=1}^{m} F\left(x_i^k\right)$$

- 适应值归一化因子
Adaptive value normalization factor

$$f^k = \min\left[1, \left|F\left(x_i^k\right) - F_{av}^k\right|\right]$$

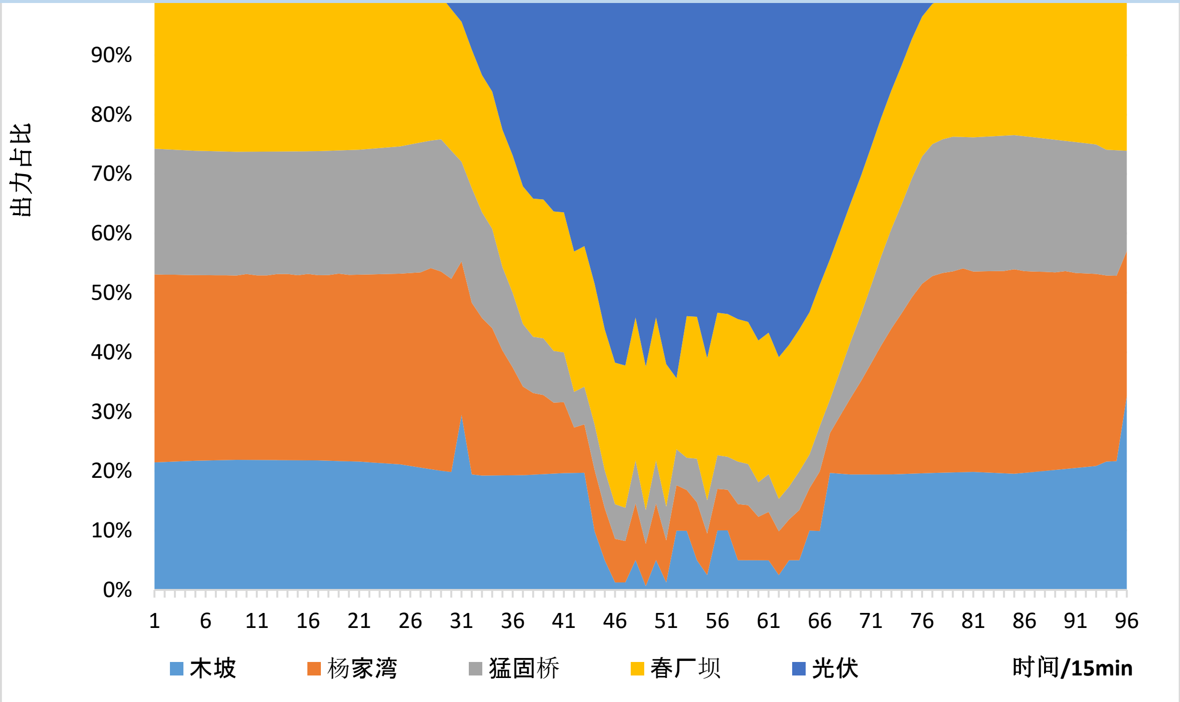


计算流程图
Calculation Flow Chart

4 源荷匹配调度模型Source-Load Matching Dispatching Model

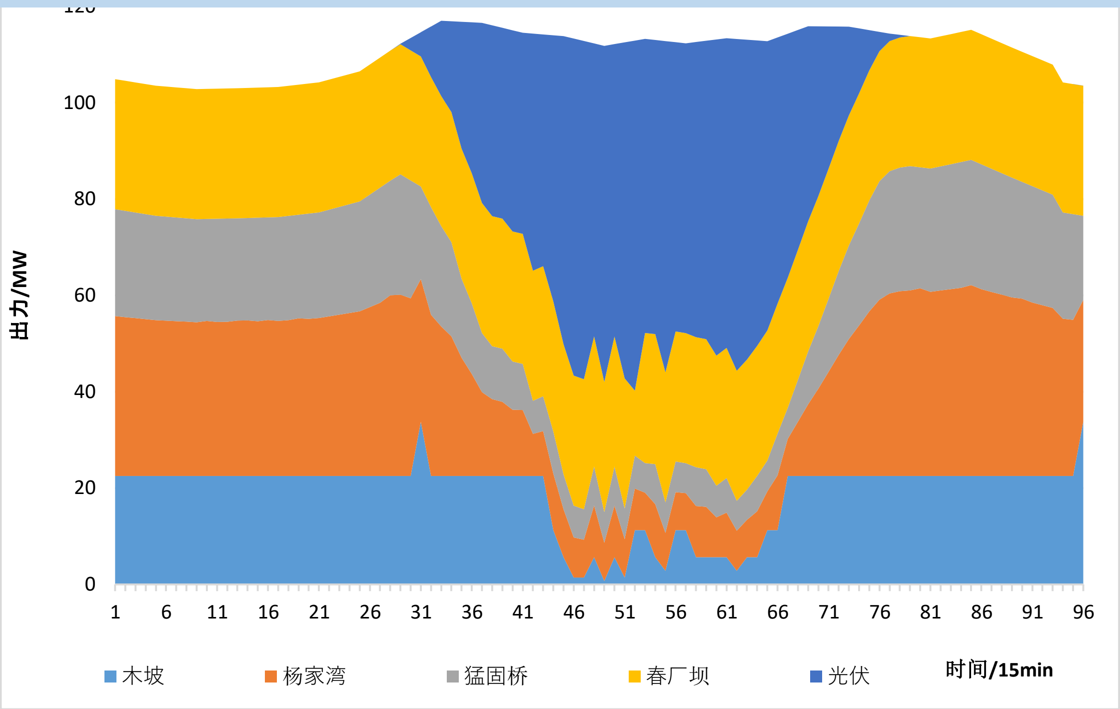
夜晚，梯级电站增加出力，以满足电网的负荷需求；在白天光伏出力较大时，为**确保水光总出力过程匹配电网负荷需求**，梯级电站减少出力。光伏出力主要**集中**于**8:00-19:00**，光伏出力**占比最高**可达**64.37%**。

During nighttime, the cascaded power plant increases its output to meet the load demand of the grid; during the daytime when the PV output is larger, the cascaded power plant reduces its output to **ensure that the total hydropower and PV power output process matches the load demand of the grid.** The PV output is mainly **concentrated** between **8:00-19:00**, and PV output represents **the highest percentage**, as high as **64.37%**.



水光互补系统发电出力占比构成

Proportion of power output



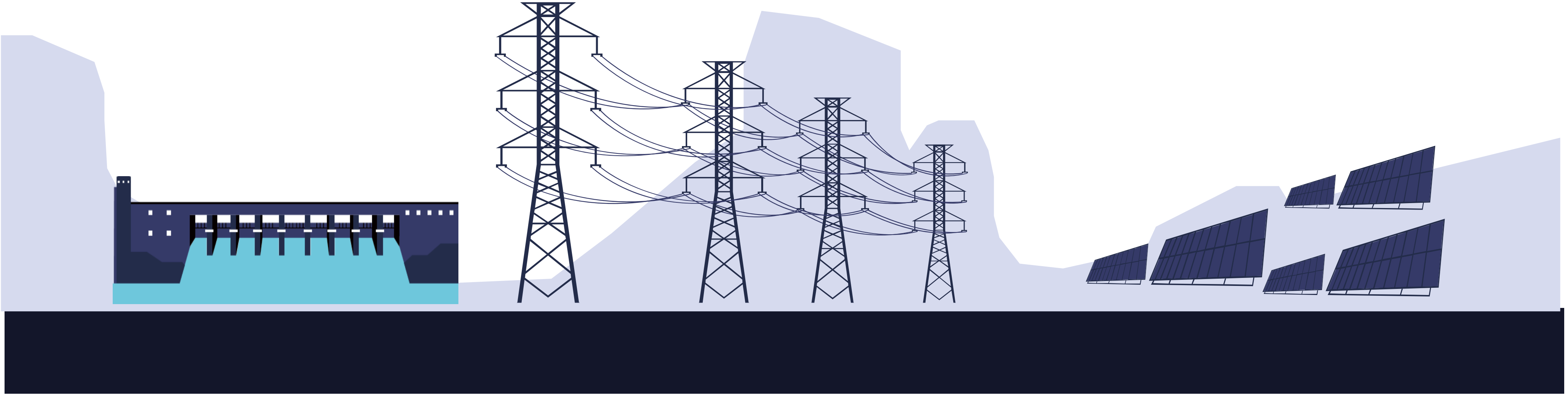
水光互补系统发电出力构成

Composition of power output

总结展望
Conclusion and Outlook

水电机组调节快速、控制灵活，是实现多能互补发电的重要纽带，研究梯级水电与风光的互补联合发电技术，对于减少可再生能源弃电，建设清洁低碳、安全高效的现代能源体系具有重要的现实价值和深远的战略意义，符合国家能源的整体发展战略，也是国家实现30·60双碳目标的重要手段。

Hydropower unit features fast regulation and flexible control, and is an important link to achieve multi-energy complementary power generation. The complementary combined generation technology of cascaded hydropower and PV is of great realistic value and far-reaching strategic significance for reducing new energy abandonment, and is an important method to achieve the carbon peak and neutrality goals by 2030 and 2060 respectively.

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