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Key technologies and the implementation of wind, PV and storage co-generation monitoring system

**Xianliang TENG (✉), Zonghe GAO,
Yingyuan ZHANG, Hua HUANG, Lili LI,
Tingting LIANG**

Abstract The coordinated control of multiple-sources including wind, photovoltaic (PV) and storage brings new challenges to traditional dispatch and control technologies. This paper firstly introduces a framework of wind, PV and storage co-generation monitoring system. Then, key technologies of co-generation monitoring system including day-ahead optimal dispatching, active power coordinated control and reactive power and voltage control are proposed. The framework and the techniques described in this paper have been applied in the National Wind, Photovoltaic, Storage and Transmission Demonstration Project of China, and their validity have been tested and verified.

Keywords Wind, photovoltaic (PV) and storage,
Co-generation monitoring system, Day-ahead optimal
dispatching, Active power coordinated control,
Reactive and voltage control, Coordination control

1 Introduction

Because of the increasing energy crisis and environmental pollution, energy saving and emission reduction are of vital importance for social development. Large-scale utilization and centralized integration of renewable energy in China becomes an inevitable trend. However, wind and solar energy are much different from conventional resources, their inherent characteristics of stochastic volatility and intermittency bring massive challenges to the dispatch and operation of power systems [1–3]. In experimental research field, large-scale energy storage technologies have drawn much attention. They are expected to be effective ways to increase the penetration of renewable energy power generation [4–7].

The National Wind, Photovoltaic, Storage and Transmission Demonstration Project has been constructed by the State Grid Corporation. The project is located in Zhangbei county, Hebei province, which aims to increase the penetration of large-scale renewable energy generation.

At present, some achievements and application practices have been realized in renewable energy generation monitoring. Reference [8, 9] analyzes the technical requirements about wind power integrating into the grid and introduces a scheme of wind farm monitoring system which aims to make wind farm a predictable, adjustable and high-quality power supply. Reference [10] presents a structure of PV generation monitoring system for data processing and analysis, which also makes remote control available. However, the system does not meet the technical requirements of PV power generation with grid-friendly interaction [3]. Besides configuration, some key technologies in grid connection and data monitoring for a small-scale wind-solar complementary generation system are described in reference [11]. However, coordination control of wind power and PV power is not involved. Reference [12] proposes a solution of operation and control for hybrid energy storage system. Wind power fluctuations can be stabilized by two controllers which are interconnected with ultra-capacitor storage and battery storage respectively. But the battery storage cannot participate in the process of power regulation more flexibly. Reference [13] discusses the general principles of control strategy for wind, PV and storage co-generation system. But a complete set of implementation scheme is not put forward.

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X. TENG, Z. GAO, Y. ZHANG, H. HUANG, L. LI, NARI Group Corporation, Nanjing 211102, China
(✉) e-mail: tengxianliang@sgepri.sgcc.com.cn
T. LIANG, Zhangjiakou Wind and Solar Power Energy Demonstration Station Co. Ltd, Hebei, China

Reference [14, 15] explains the operation and management technologies for large-scale wind power dispatch and control in provincial dispatching center. Control schemes of AGC and AVC are discussed. And the framework of on-line power and voltage control to wind farm are put forward at the same time.

In general, application of wind PV and storage co-generation monitoring system is still concerned with the theoretical research and simulation phase. There are few engineering applications and operating experiences. It is expected to do further research in models and strategies of multiple-source complementary coordination control.

Based on the National Wind, PV, Storage and Transmission Demonstration Project, this paper mainly studies the coordinated operation mechanism and focuses on three key dispatching technologies discussed in the following. In addition, the proposed technical schemes have been tested and verified in the practical project.

1) Day-ahead optimal dispatching: An optimization model aiming to maximize the benefits of the co-generation system is given in this paper. Meanwhile, penalties for multi-point coupling fluctuations of generating curves are considered and are added to the optimal object.
2) Active power coordinated control: An active power coordinated control strategy is proposed to satisfy different operation requirements including co-generation output fluctuation smoothening, planned generation output tracking and frequency regulation participating. Taken co-generation and single plant into account, this paper designs various combinational control modes, which can be flexibly configured.
3) Reactive power and voltage control: The general ideas for coordinated control are presented as follows. Wind turbines, PV inverters and storage devices are given priority during the regulating process. Static var generator (SVG) is expected to respond as quickly as possible. Capacitor switching acts as a supplementary method. Cooperative and coordinated control of reactive power resources can be realized in multiple modes, such as continuous or discrete mode, high speed or low speed mode and voltage command or reactive power command mode.

2 Framework of the wind, PV and storage co-generation system

The National Wind, PV, Storage and Transmission Demonstration Project plans to construct 500 MW wind farms, a 100 MW PV power station and a corresponding energy storage plant. The first-phase project was completed and put into operation on December 25, 2011. Construction of the first-phase project includes 100 MW wind farms, a 40 MW PV power station, a 20 MW energy storage plant and a 220 kV smart substation. At present, the project is the largest comprehensive renewable energy utilization platform worldwide, aiming to make the renewable energy involved predictable, controllable and dispatchable. Besides, the grid capability for large-scale renewable energy integrating can be effectively improved.

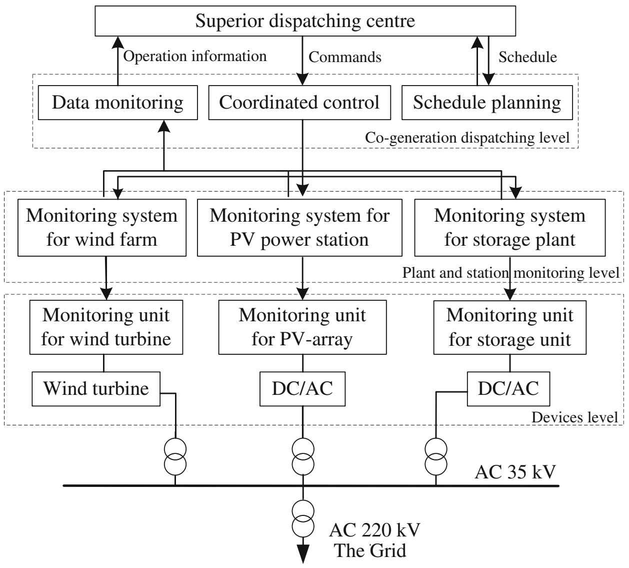
Superior dispatching centre
Operation information
Commands
Schedule
Data monitoring
Coordinated control
Schedule planning
Co-generation dispatching level
Monitoring system for wind farm
Monitoring system for PV power station
Monitoring system for storage plant
Plant and station monitoring level
Monitoring unit for wind turbine
Monitoring unit for PV-array
Monitoring unit for storage unit
Wind turbine
DC/AC
DC/AC
Devices level
AC 35 kV
AC 220 kV
The Grid

Fig. 1 Framework of the wind, PV and storage co-generation system

The general framework of the demonstration project consists of three levels as shown in Fig. 1. They are co-generation dispatching level, plant and station monitoring level, and devices level, among which, co-generation dispatching level is a bridge connecting the co-generation system to the superior dispatching centre. On one hand, this level designs open and coincident models of the co-generation system and provides operation analysis support for superior dispatching centre. On the other hand, as a controlling centre of the whole demonstration project, this level carries on intelligent analysis and decision-making, and the coordinated control among wind farms, PV power station and storage plant is realized. *Plant and station monitoring level* is used to monitor each plant and upload real-time operation information of every device. This level also receives control commands sent by co-generation dispatching level and distributes to control units in devices level simultaneously.

Wind, PV and storage co-generation panoramic monitoring system is developed and applied in co-generation dispatching level. The monitoring system offers a variety of advanced applications which mainly include Day-ahead optimal dispatching, active power coordinated control,

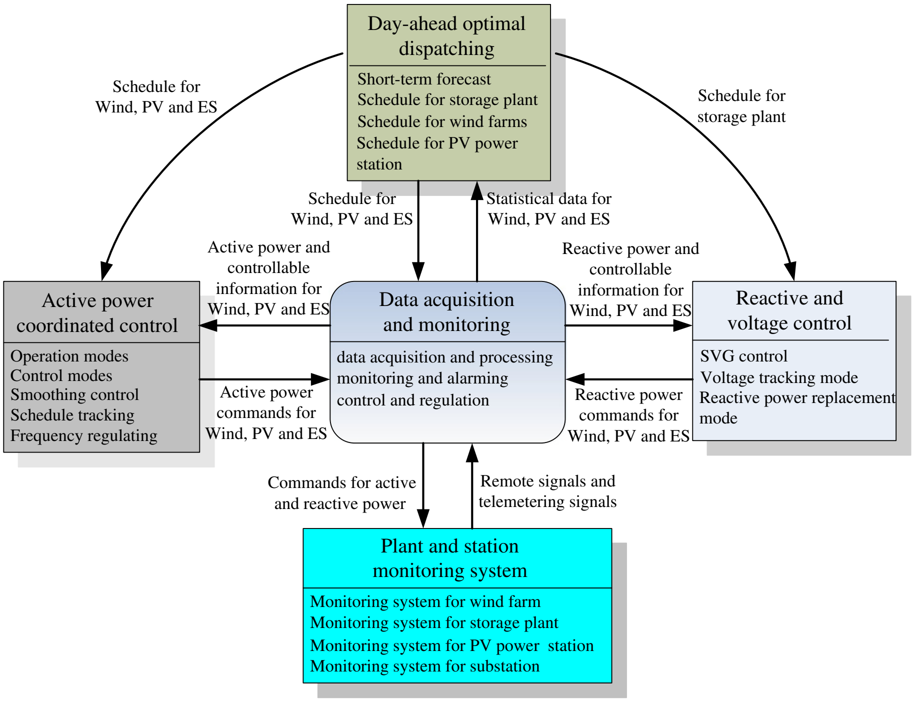
Day-ahead optimal dispatching
Short-term forecast
Schedule for storage plant
Schedule for wind farms
Schedule for PV power station
Schedule for Wind, PV and ES
Schedule for storage plant
Schedule for Wind, PV and ES
Statistical data for Wind, PV and ES
Active power and controllable information for Wind, PV and ES
Reactive power and controllable information for Wind, PV and ES
Active power coordinated control
Operation modes
Control modes
Smoothing control
Schedule tracking
Frequency regulating
Data acquisition and monitoring
data acquisition and processing
monitoring and alarming
control and regulation
Reactive and voltage control
SVG control
Voltage tracking mode
Reactive power replacement mode
Active power commands for Wind, PV and ES
Reactive power commands for Wind, PV and ES
Commands for active and reactive power
Remote signals and telemetering signals
Plant and station monitoring system
Monitoring system for wind farm
Monitoring system for storage plant
Monitoring system for PV power station
Monitoring system for substation

Fig. 2 Logical relationship among each applications of the wind, PV and storage co-generation panorama monitoring system

reactive power and voltage control, etc. Logical relationship among those applications is shown in Fig. 2.

3 Key technologies and their application

3.1 Day-ahead optimal dispatching

There are two key requirements of wind, PV and storage co-generation system in the day-ahead optimal dispatching. One is to keep generation curve smooth, which means to smooth out the fluctuations caused by the intermittent energy generation using bidirectional characteristics of storage devices. The other is to increase the integration capacity of intermittent energy. Based on short-term prediction of renewable energy generation, reasonable schedules are drawn up and expected to ensure maximum integration capacity of renewable energy.

3.1.1 Problem formulation

Smoothing model could be achieved in two ways: constrained or objective. The latter model is adopted here.

1) Objective function
   The objective of co-generation schedule is to maximize the deviation between integration revenue of the co-generation system and penalty cost of power fluctuation:

$$\max f = \sum_{t=1}^{T} [C_t P_t - \Delta S_t] \tag{1}$$

where T is the interval numbers in a schedule period; P_t is the total co-generation schedule over time interval t; C_t is the generation revenue per unit; ΔS_t is the penalty cost of power fluctuation. The objective is a superposition of generation revenue and penalty cost. Since generation revenue can be used to measure the integration benefits of co-generation directly, the penalty cost has also been given certain economic significance. The penalty cost is the mechanical wear of thermal units, caused by the regulation of power output to meet the requirement of co-generation schedule.

In order to ensure that the generation revenue and penalty cost are in the same dimension, the penalty cost is normalized to the dimension of generation revenue. The formulation is

$$\Delta S_t = \lambda C_t \Delta_t \tag{2}$$

where Δ_t is the power fluctuation of co-generation schedule over time interval t and obtained by formulating a smoothing model for co-generation schedule. $\lambda \in (0, 1)$ is the offset scale factor of generation revenue per unit caused by power fluctuation. Thus, when co-generation schedule fluctuates, the total revenue will be reduced after superimposed on the penalty cost and will in turn suppress the fluctuation of the schedule.

2) Constraints

The main constraints are listed as follows.

a) System power balance

$$\sum_{w=1}^{N_w} P_{w,t} + \sum_{v=1}^{N_v} P_{v,t} + P_{c,t} + P_{d,t} = P_t \quad (3)$$

where N_W is the number of wind farms; $P_{w,t}$ is the power output of the wind farm w over interval t; N_V is the number of PV power stations; $P_{v,t}$ is the power output of the PV power station v over interval t; $P_{c,t}$ is the power of storage plant in charging mode over interval t; and $P_{d,t}$ is the power of storage plant in discharging mode over interval t.

b) Wind generation power output

$$0 \le P_{w,t} \le P_{0,w,t} \quad (4)$$

where $P_{0,w,t}$ is the forecasting power output of the wind farm w over interval t.

c) PV generation power output

$$0 \le P_{v,t} \le P_{0,v,t} \quad (5)$$

where $P_{0,v,t}$ is the forecasting power output of the PV power station v over interval t.

d) Inverter power output of storage plant in charging and discharging mode

$$-P_{inv} \le P_{c,t} \le 0 \quad (6)$$

$$0 \le P_{d,t} \le P_{inv} \quad (7)$$

where P_{inv} is the allowed inverter power output of storage plant.

e) Capacity constraints of storage plant

Charging energy for each interval:

$$E_{c,t} = \alpha P_{c,t} dt \quad (8)$$

Discharging energy for each interval:

$$E_{d,t} = \beta P_{d,t} dt \quad (9)$$

where α is the efficiency coefficient in charging mode; β is the efficiency coefficient in discharging mode.

The stored energy of storage plant at the end of each interval is

$$E_t = E_{t-1} + E_{c,t} - E_{d,t} \quad (10)$$

$$E_0 = E_{ini} \quad (11)$$

where E_{ini} is the initial stored energy of storage plant.

Capacity limits:

$$E_{\min} \le E_t \le E_{\max} \quad (12)$$

where $E_{\max}$ and $E_{\min}$ are the upper and lower capacity limit of storage plant respectively.

3) Smooth modeling

For co-generation system, its modeling solution should consider multi-period coupling changes to avoid sharp swings of total power output. A power fluctuation penalty is added into the objective function. There are two methods for modeling of the penalty: three-point coupling smoothing model and two-point coupling smoothing model.

a) Three-point coupling smoothing model

This model considers the changes of the co-generation power output during three adjacent periods. And the mathematical model is

$$\Delta_t = |(P_{t+1} - P_t) - (P_t - P_{t-1})| \quad (13)$$

It's mainly used for reducing the frequency of fluctuations.

b) Two-point coupling smoothing model

This model considers the changes of the co-generation power output during two adjacent periods. And the mathematical model is

$$\Delta_t = |P_t - P_{t-1}| \quad (14)$$

This model is mainly used for reducing the magnitude of fluctuations.

Linear programming (LP) algorithm has been widely applied in practical systems because of its advantage of fast computational speed and reliable convergence. After linearization of optimization model, this paper solves the optimal problem by adopting a commercial package CPLEX. CPLEX is a sophisticated and computationally efficient solution that can handle thousands of variables.

3.1.2 Case study

Based on measured data of the demonstration project, a study case is constructed and a series of numerical analysis is carried out. The case includes two wind farms with installation capacity of 100 MW, a PV power station with installation capacity of 40 MW, and a storage power plant with capacity of 20 MW. The co-generation system is connected to the grid via a 220 kV substation. On the basis of daily forecasting data of wind power and PV power, day-ahead generation scheduling is optimized and drawn up in 96 periods. The time period is 15 min.

Related information of the storage plant is described as follows. Upper and lower capacity limits are 50 MWh and 5 MWh respectively. Initial stored energy is 10 MWh. Allowed maximum inverter power output is 50 MW. The efficiency coefficient in charging mode is 0.8, while the efficiency coefficient in discharging mode is 1.

Predictive power outputs of wind farms and PV power station are shown in Fig. 3.

Fig. 4 shows the accumulated forecasting power of wind farms and PV power station. The optimized total power of the co-generation system is drawn as well. The charging and discharging result of the storage plant is shown in Fig. 5. Stored energy of the storage plant is described in Fig. 6.

The above results show that the optimized fluctuation of accumulated power of wind farms and PV power station is restrained by the storage plant. The power output of the co-generation system keeps at a certain constant value. The curve of total power output is comparatively smooth and ideal.

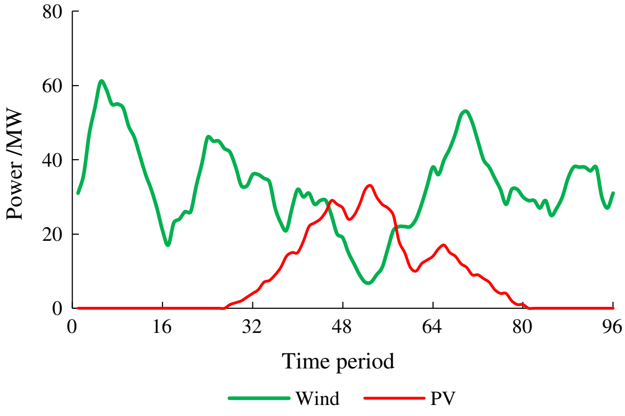

Fig. 3 Forecast of renewable energy generation

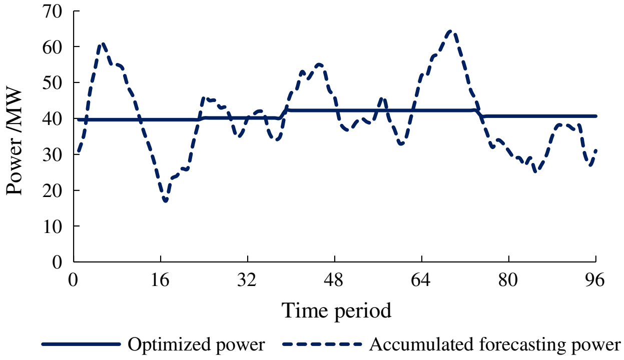

Fig. 4 Optimized results of the co-generation system

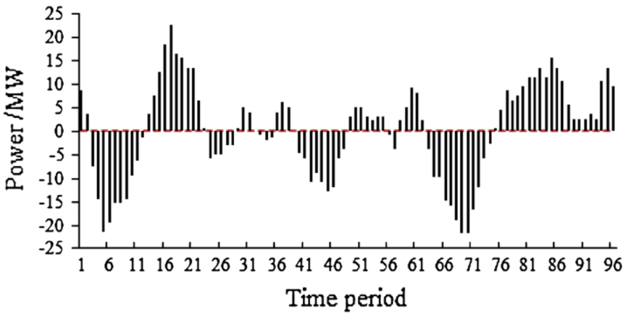

Fig. 5 Optimized charging and discharging result of the storage plant

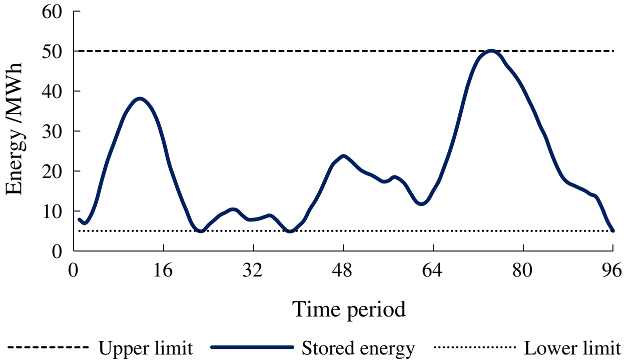

Fig. 6 Stored energy of the storage plant

Fig. 6 shows that stored energy of the storage plant reaches its lower limit at period 23 and 39, and it reaches the upper limit at period 74. These limitations lead to the variations of the co-generation system power output.

3.2 Active power coordinated control

Active power coordinated control is utilized for further promoting the grid-friendly characteristic of the co-generation system.

3.2.1 Overall scheme

Real-time operation of the co-generation system involves various operating configurations. Its control objection may keep changing according to different power regulation demands. They all raise the difficulty of dispatching. As a result, this part presents two fundamental control modes: plant and station control mode, co-generation control mode.

Regarding diverse features and control requirements, control modes for wind farms, PV power station and storage plant are designed to cope with different scenarios. These control modes include output maximization mode, schedule tracking mode, output limit mode, reserve mode and automation mode.

Co-generation control mode is used to describe the global run mode of the co-generation system. In this paper, a kind of co-generation operation with coordinated multi-objective control is realized, the power generation resources are all combined properly. For each operation mode, corresponding control modes are listed in Table 1.

3.2.2 Control strategy

The control objects are determined by the operation mode, while the control objectives are decided by the

Table 1 List of operation and control modes

Operation modes	Control modes			
Wind-PV-ES	Smoothing	Tracking AGC attaching superior dispatching centre	Tracking schedule	Tracking a setting object
Wind-ES PV-ES	Smoothing	Tracking schedule	Tracking a setting object	
Wind-PV Wind alone PV alone	Free power generation	Tracking schedule	Tracking a setting object	
Storage alone	Frequency regulating	Tracking schedule	Tracking a setting object	

control mode. In accordance with features among objective functions, control modes can also be distinguished as smoothing control mode and tracking control mode.

1) Smoothing control mode
   In smoothing control mode, the storage plant is used to smooth the fluctuations of power output. The fluctuation is possibly caused by wind power, PV generation, or wind and PV co-generation. For the storage plant, a state of charge (SOC)-feedback, which is built upon traditional one-order low pass filter to avoid excessive charge-discharge, is added to the control loop. The control block diagram is interpreted in Fig. 7.
   where P_{wp} is the power input of wind and PV co-generation; P_{wpb} is the power output of wind, PV and storage co-generation; P_{b0} is the charge-discharge power which is obtained by one-order low pass filter; P_b is the revised charge-discharge power which is gained by accounting SOC; T is the time constant of one-order low pass filter; B is the compensation coefficient; K is the feedback gain; and O_{offset} is the offset compensation and used to guarantee the storage devices to be in the optimum area.
2) Tracking control mode
   Wind, PV and storage co-generation system can provide steady power output as planned. But the premise is the coordination with the storage plant and real-time bias compensation. This part puts forward a kind of tracking control strategy. The principle of the strategy is to bundle wind energy generation and PV generation, then decouple the control of storage energy. The intermittent energy generation plants and the storage plant have relatively independent control target.
   In order to maximize the utilization of wind and PV resources, wind farm and PV should produce maximum power if the storage plant has sufficient storage space. Thus, for wind and PV co-generation, the objective function can be written as

$$P_{wp\_des}(t) = P_{ref}(t) + \Delta P_{b\max}(t) \tag{15}$$

   where $P_{wp\_des}(t)$ is the ideal objective of wind and PV co-generation at period t; $P_{ref}(t)$ is the tracked reference objective at period t; and $\Delta P_{b\max}(t)$ is the allowed maximal charged power of the storage plant at period t.
   After decoupling, the real-time output objective of the storage plant is the deviation between real-time co-generation power and reference objective. The ideal adjustment can be written as

$$\Delta P_b(t) = P_{ref}(t) - P_{wpb}(t) \tag{16}$$

   where $\Delta P_b(t)$ is the ideal adjustment of the storage plant at period t; and $P_{wpb}(t)$ is the output of wind and PV co-generation at period t.

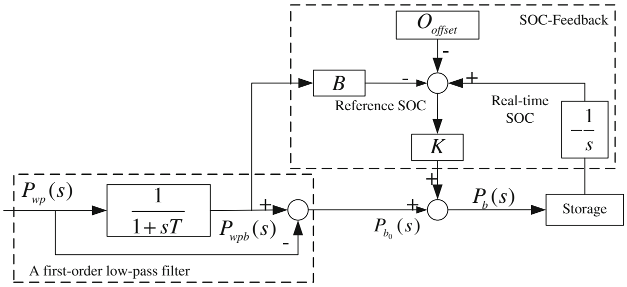

Fig. 7 Block diagram of the SOC-feedback control

3.2.3 Application

1) The effect of smoothing control mode
   In Wind-PV-ES operation mode, power output with smoothing control mode (within an hour) is shown in Fig. 8.
   The grid-connected technology specification of wind farm and PV power station has clarified the maximum variation of power fluctuations, but the degree of fluctuations is not evaluated. To quantify the smoothing effect of the storage plant, a volatility index $\boldsymbol{\alpha}$ is introduced.

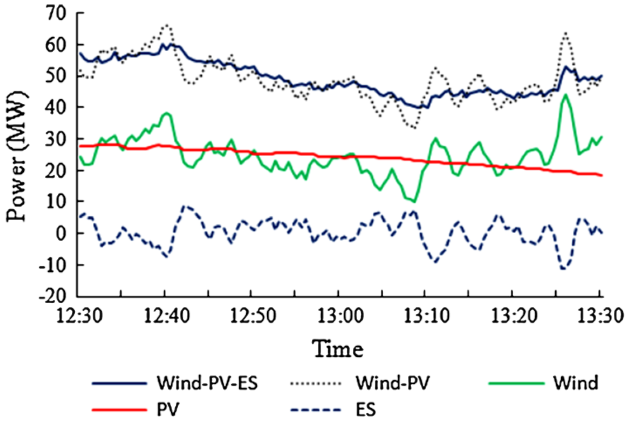

Fig. 8 Power output of Wind-PV-ES co-generation in smoothing mode

$$\alpha = \frac{P_{\max,1\min} - P_{\min,1\min}}{P_{avg,1\min}} \times 100\% \tag{17}$$

where $P_{\max,1\min}$ is the upper limit of power output within 1 min; $P_{\min,1\min}$ is the lower limit of power output within 1 min; $P_{avg,1\min}$ is the average power output within 1 min.

Fig. 9 draws the volatility index α of Wind-PV-ES co-generation power output before and after smoothing. It can be found that the volatility index of Wind-PV co-generation power output is generally around 10%. After smoothing, the average volatility index decreases from 7.97% to 4.39%. It shows that the volatility index is notably improved.

2) The effect of tracking control mode

In Wind-PV-ES operation mode, the effect of tracking control mode (within an hour) is shown in Fig. 10.

In Wind-PV-ES operation mode, control precision within an hour in tracking control mode is listed in Table 2.

As is shown above, in case the regulation reserve of the storage plant is sufficient, control errors within an hour are all below 10%. The proportion of the points with a control error percent below 5% is 98.35%. The proportion comes to 92.56% with a control error below 3%. This verifies the effectiveness of the control. The power output characteristic of the Wind-PV-ES co-generation system can be similar to that of the conventional power sources.

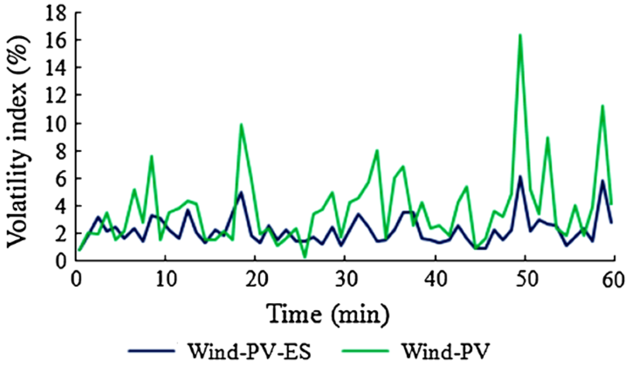

Fig. 9 Comparison of volatility

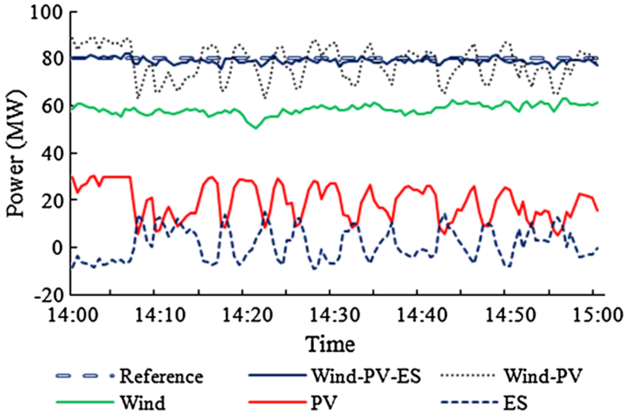

Fig. 10 Power output of Wind-PV-ES co-generation in tracking mode

Table 2 Control precision in tracking mode

	Control error/η		
	<10%	<5%	<3%
Percent	100%	98.35%	92.56%

3.3 Reactive power and voltage control

Each reactive power regulating device has its difference in regulating performance in the co-generation system. So a major point of this part is to research the coordinated control among various reactive power sources.

3.3.1 Overall scheme

According to the hierarchical voltage regulation principle [16], the structure of reactive power and voltage control can be divided into two levels in this system.

1) Primary control: In this level, SVG attempts to compensate voltage fluctuation caused by rapid variations of renewable energy. It is expected to maintain the constancy of the voltage of 35 kV bus. This cycle will be in milliseconds.
2) Secondary control: The object is to keep the voltage of the injection point at the desired reference values. It is realized through coordinated control among SVGs, wind turbines, inverters and capacitors. The control

cycle will be set up from 30 s to 5 min.

SVG is expensive and limited by its installed capacity, which makes it a precious reactive power resource. Thus, the general ideas for coordinated control are as follows. Wind turbines, PV inverters and storage devices are given priority during regulating process. SVG is expected to respond as soon as possible. Capacitor switching acts as a supplementary method. Taking full advantage of reactive power regulation capability of renewable energy generation, we can own maximum dynamic reactive power reserve of SVG and carry out minimum number of capacitors action.

3.3.2 *Control strategy*

Reactive power and voltage control can be divided into two steps: statistical calculation for regulatory demand and assignment among multi-sources as illustrated in Fig. 11.

Assignment strategy among multi-sources is the core link throughout this process. Reactive power demand is distributed among those reactive power sources in reasonable orders. There are two different implementations that include voltage tracking mode and reactive power replacement mode. The latter one is expected to keep maximum dynamic reactive power capability of SVG and provide constant total reactive power.

Based on calculation results, adjustment target for each feeder will be determined according to equal power factor principle.

3.3.3 *Application*

1) The effect of voltage tracking mode

   Fig. 12 shows the effect of voltage tracking control. Take the following case as an example. The reference voltage was changed from 230 kV to 225 kV at 14:31:10 on December 23, 2011. The dead zone of command was set at 1 kV. At this point, real-time voltage was 230.5 kV, with a 5.5 kV deviation from reference voltage, which obviously exceeded the dead zone. Hence the co-generation monitoring system started to control immediately. At 14:34:10, real-time voltage was adjusted to 230.5 kV, with a 0.5 kV deviation from reference voltage which met the control requirements. Meanwhile, reactive power of the injection point was varied from −18 MVar to −30 MVar.

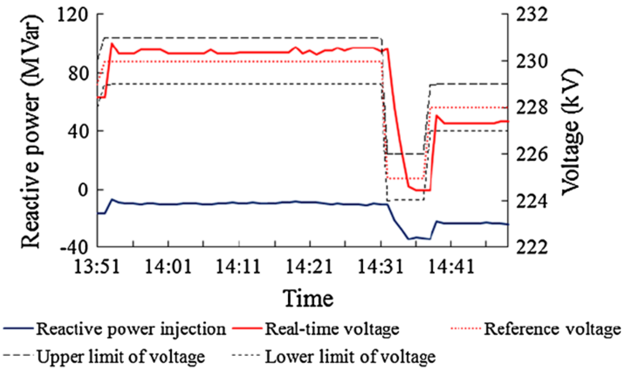

Fig. 12 Effect of voltage tracking mode

   Fig. 13 shows the control sequence of all devices in the same section. Voltage of the 35 kV bus, which connects with SVG, dropped gradually from 37.2 kV to 35.7 kV. Reactive power of Xiaodongliang wind farm varied from 3.8 MVar to −3 MVar. And the voltage of PV power station decreased from 5 MVar to 0 MVar.

   It can be concluded that the above-mentioned regulating process can rapidly track the voltage of the injection point at 220 kV bus. And the control effect is satisfying. The rate of regulation is greater than 1 kV/min.

2) The effect of reactive power replacement mode

   While active power is stable, co-generation monitoring system will start to adjust low-speed reactive power resources to substitute for capacity of SVG, thus it increases the dynamic reactive power reserves. The capability to smooth the rapid voltage fluctuations will be reserved consequently. Fig. 14 shows the control sequence of all devices on Dec.19, 2011.

   During that period, active power of the co-generation system was relatively steady. The voltage of the 35 kV bus remained around 37 kV. Reactive power of the SVG

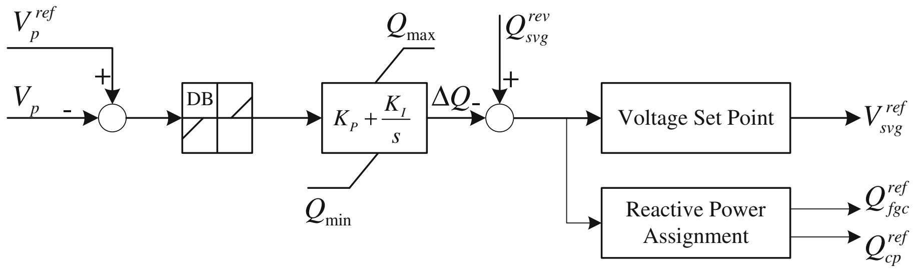

Fig. 11 Schematic diagram of reactive power and voltage control

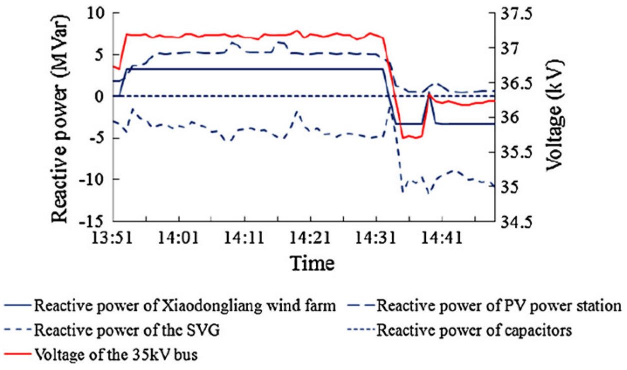

Fig. 13 Control sequence of reactive power sources for voltage control

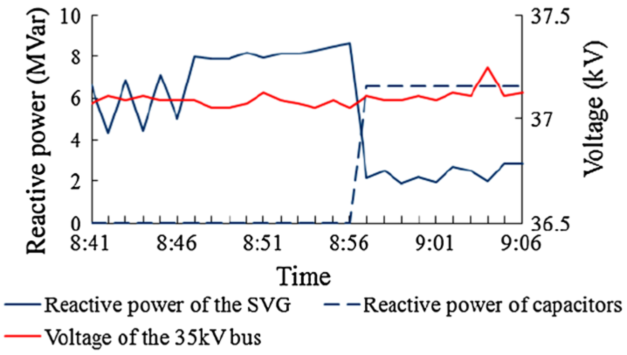

Fig. 14 Control sequence of reactive power sources under reactive power replacement mode

kept around 8 MVar before 8:56. At 8:56, capacitors were ordered to put into regulation, reactive power of the SVG started to adjust and gradually dropped to 2 MVar. In other words, dynamic reactive power capability of SVG was improved.

4 Conclusions

Wind, PV and storage co-generation monitoring system has been implemented in the demonstration project. With several months of trial operation, the project is stable and reliable. Complementary advantages of each participant are made to the most. Power output of the co-generation system is grid-friendly and is similar to conventional power sources. Regulation characteristic of grid-connected voltage is improved. Grid capability to accept renewable energy is effectively improved.

Both theory and practice prove that it is feasible to make use of renewable energy resources through wind, PV and storage co-generation mode. This will be one of the developing directions for utilization of renewable energy resources and a demonstrative case for large-scale renewable energy power integration.

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Xianliang TENG received the B.E. degree in 2000 from Zhengzhou University of Technology and M.E. degree in 2011 from Southeast University. Currently, he is working at NARI Group Corporation, China. His work has been in power system dispatch and control, renewable energy generation and its integration.

Zonghe GAO received the M.E. degree in 1989 from State Grid Electric Power Research Institute (SGEPRI), Nanjing, China. Currently, he is the Managing Director of Nanjing Power Grid Dispatching & Control Technology Branch Company, NARI Group Corporation. His work has been in the power system dispatch and control.

Yingyuan ZHANG received the Ph.D degree in 2011 from Hefei University of Technology, Anhui, China. Currently, she is working at NARI Group Corporation, China. Her work has been in the power system dispatch and control.

Hua HUANG received the M.E. degree in 2001 from Huazhong University of Science and Technology, Wuhan, China. Currently, he is working at NARI Group Corporation, China. His work has been in the power system dispatch and control, especially voltage control and reactive power optimization.

Lili LI received the M.E. degree in 2011 from State Grid Electric Power Research Institute (SGEPRI), Nanjing, China. Currently, he is working at NARI Group Corporation. His work has been in the power system operation and optimization.

Tingting LIANG received the B.E. degree in 2004 from Northeast electric power University, Jilin, China. Currently, she is working at Zhangjiakou Wind and Solar Power Energy Demonstration Station Co. Ltd. Her work has been in the renewable energy generation and its integration.