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Theories and methodology of complementary hydro/photovoltaic operation: Applications to short-term scheduling

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The recently implemented Longyangxia 320 MW complementary hydro/photovoltaic (PV) project provides a novel operation mode for utility-scale PV power plants. In this paper, the principle of complimentary hydro/PV operation is presented. In short-term scheduling, hydropower can improve the power quality of PV by compensating for the sawtooth-shaped power output curve of PV and for the intermittent and random output of PV. Conversely, in mid- to long-term scheduling and during peak load regulation, PV can compensate the hydro energy deficiency of hydropower via the electricity generated. The concept of virtual hydropower is also proposed. The ability of hydropower to compensate for PV is analyzed, and curtailment situations for solar energy and water as well as their causes are detected. Finally, a calculation model for complementary hydro/PV operation is developed based on the Longyangxia project. The results show that complementary hydro/PV operation can remarkably improve the power quality of PV and is better able to reduce the peak load than a standalone hydropower plant.
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I. INTRODUCTION

Solar energy is clean, environmentally friendly, and renewable.[1,2] Its advantages, including an inexhaustible supply, low prices, and lack of pollution, make photovoltaics (PV) more competitive than other renewable energy sources (RESs).[3] Along with the gradual exhaustion of fossil fuel energy and global climate changes, there is an urgent need to develop PV power generation to optimize the energy supply and reduce greenhouse gas (GHG) emission. In China, the PV industry started up in the 1970s and maintained steady growth over a long period. Since 2004, the Chinese PV industry has experienced tremendous growth, and with annual growth rates exceeding 100% for several years, its production capacity was ranked highest in the world in 2008.[4] Many utility-scale PV power plants have been constructed throughout China (especially in northwestern China) since 2009 due to policy incentives. By the end of 2014, the total installed capacity of PV interconnected with power systems reached 28.05 GW in China, including 23.38 GW through utility-scale PV plants and 4.67 GW through distributed PV generation. The annual energy production is nearly 25 GW h. The PV capacity newly installed in 2014 was 10.6 GW, which accounted for nearly one fifth of newly installed PV capacity in the world.[5]

PV output is random and intermittent due to a number of random factors, such as unstable meteorological conditions and the day/night cycle. If PV is directly connected with the power system, there will be adverse impacts on the stable operation of the system, and additional difficulties will be caused by regulating the peak load to include PV power in the system's spinning reserves.[6] To obtain a more continuous power supply, Glasnovic and Margeta combined a

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reversible hydroelectric power plant and a PV power plant as an integrated energy-producing system. Solar energy acts as the entire energy input to activate the system, and electric energy generated by PV is used to pump water from the lower reservoir to the upper reservoir; then the stored water is discharged to produce continuous electricity according to the needs of consumers. However, a reversible hydropower plant must be constructed to realize such a system.[7] Kenfack *et al*. introduced a microhydro-PV-hybrid system for remote rural areas in Cameroon. Solar energy is mainly employed to compensate for the deficiency of hydro energy in the dry season, thus helping to maintain a constant level of electricity production. Diesel generators acting as a back-up are also included in the system.[8] Alsayed *et al*. proposed a PV-wind turbine grid-connected system. Multicriteria decision analysis considering technical, economic, social, and environmental criteria simultaneously is adopted to obtain the optimal sizing and balance between PV and wind power.[9] Lund analyzed the large-scale integration of PV, wind power, and wave power into a Danish power system. With a goal of benefiting from the different fluctuating patterns of various sources of renewable energy, the optimal mixtures of renewable energy sources are also identified.[10]

Practical hybrid systems mainly supply energy to standalone power systems or isolated consumers. Fossil fuel power plants or energy storage infrastructure (such as pump storage hydro, compressed air, flywheel, flow battery, and superconducting magnetic energy) are also indispensable for providing a continuous and reliable power supply. However, once solar and wind energy are exploited at the utility scale, current energy storage technologies are not able to economically stabilize the unstable output of RESs. At present, utility-scale PV and wind power plants are typically directly interconnected with the power system, and substantial spinning reserves are required, which results in a more extended system and higher operation cost and risk. The situation will become increasingly worse as more RES power penetrates the system. Power producers could improve upon the business-as-usual scenario by stabilizing the output of RESs locally such that qualified and desirable electricity can be provided for the power system.

Hydropower has several advantages such as quick startup and shutdown and flexible adjustment. It invariably plays a critical role in covering the peak load and providing emergency reserves for the power system and can be regarded as an elastic power supply.[11] If a hydropower plant is located near a PV power plant, these two types of RESs may operate in a complementary mode, thus improving the power quality of PV.

The Longyangxia 320 MW PV plant was commercially implemented at the end of 2013, and a novel operation mode has been utilized in the project, namely, complementary hydro/PV operation. The innovative operation can be summarized as follows: (1) electricity generated by the PV plant is transmitted to the Longyangxia hydropower plant via 330 kV high-voltage transmission lines; (2) the PV plant works together with other four hydropower units to accomplish the production task scheduled by the power system; and (3) the random output curve of PV can be stabilized by rapidly adjustable hydropower units, and the output of PV and hydropower bundled together will be integrated into the system. Despite its success in practice, the novel complementary hydro/PV operation still lacks theoretical support. Thus, a theoretical study of complementary hydro/PV operation is necessary to develop basic theories of hydro/PV complementarity and to satisfy the demand for the profitable construction and operation of utility-scale PV plants in the future.

II. PRINCIPLE OF COMPLEMENTARY HYDRO/PV OPERATION

A. Complementarity of hydropower and PV

Hydro energy is renewable and can be stored by reservoirs. Due to its flexibility in increasing and decreasing power output, hydropower is able to compensate for highly variable RESs promptly. Other outstanding advantages include nearly zero greenhouse gas emission, low cost, high efficiency, and contribution to the comprehensive utilization of water resources (such as flood control, irrigation, shipping, and aquaculture).

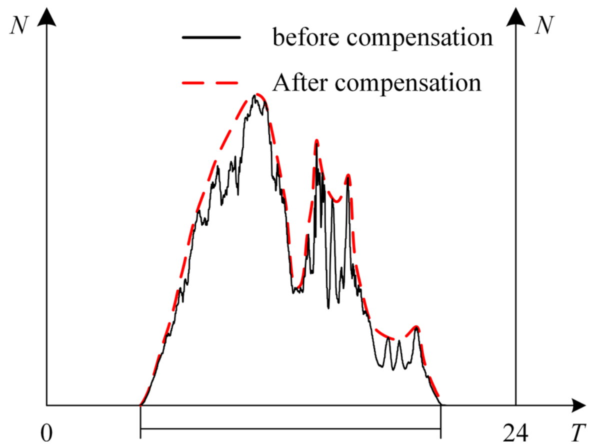

FIG. 1. First-stage compensation of PV through hydropower.

PV possesses relatively permanent, widespread, clean, and enormous energy sources. However, the power output of PV is intermittent and random due to the instability of the solar energy reaching the ground.

According to the characteristics of hydropower and PV outlined above, the complementarity of these two types of renewable energy can be expressed as follows: hydropower compensates for the unstable output of PV by its rapidly adjustable output, whereas PV compensates for the hydro energy deficiency of hydropower in mid- to long-term scheduling and in satisfying the peak load.

1. Compensation of PV by hydropower

Compensation of PV by hydropower is a two-stage process. In the first stage, through the small movement of guide vanes, hydropower units are utilized to smooth the sawtooth-shaped output curve of PV, as shown in Fig. 1. In the second stage, depending on the amount of hydro energy stored in reservoirs as well as the rapid output change of hydropower units, hydropower units are able to eliminate the randomness and intermittency of the PV output and help maintain a constant total output, as shown in Fig. 2.

Therefore, through the two-stage complementary process, the highly variable output of PV can be moderated and the power quality can be improved, thus providing a solid foundation for the integration of utility-scale PV into the power system.

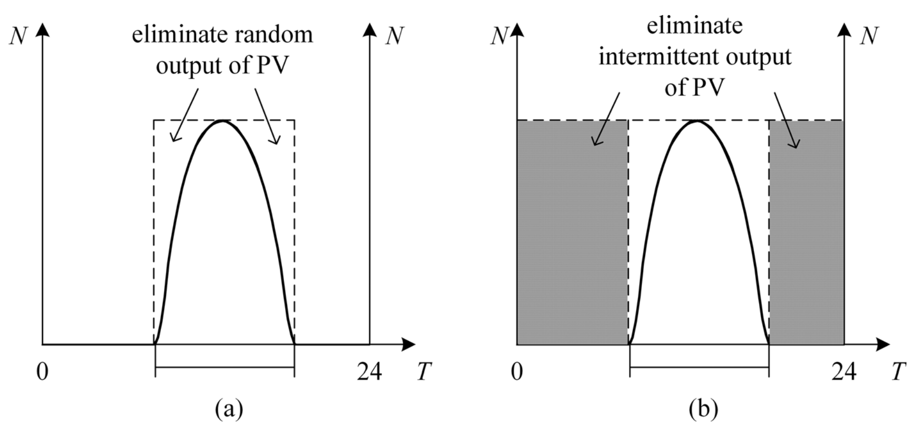

FIG. 2. Second-stage compensation of PV through hydropower. In (a), the randomness of the PV output is eliminated, and in (b), the intermittency of the PV output is eliminated.

2. Compensation of hydropower through PV

Water storage in a reservoir is dominated by natural runoff; however, seasonal and interannual variations in runoff are notable. According the quantity of natural runoff, there are wet years, normal years, and dry years on the interannual timescale, and one year is further divided into wet season and dry season.[12] Electricity generated by hydropower relies on the water available in reservoirs; therefore, units are able to generate more electricity in a wet year or wet season, whereas less electricity is generated in a dry year or dry season. In contrast, interannual variations in solar energy are minor. For example, in Gonghe County, Qinghai Province, where the Longyangxia 320 MW PV plant is located, the ratio of the maximum to minimum annual energy production by PV is only 1.04. Moreover, more electricity is generated by PV in the dry season than in the wet season due to the influence of cloud thickness. Thus, in a dry year and dry season, PV can compensate for the hydro energy deficiency of hydropower, whereas in a wet year and wet season, hydropower can support PV, thus forming the seasonal and interannual complementarity of hydropower and PV. When PV operates in the daytime, hydropower reduces its output and more hydro energy is reserved in the reservoir. In the evening and peak load hours, hydropower can compensate for the intermittent output of PV and further satisfy the peak load by consuming the additional reserved hydro energy to increase its output. Therefore, when coordinated with PV, hydropower can more flexibly dispatch the hydro energy, and more favorable performance on peak load regulation will be obtained.

In summary, the complementarity of hydropower and PV lies in the following:

(1) In short-term scheduling, hydropower supports PV through its rapidly adjustable power output.
(2) In mid- to long-term scheduling and peak load regulation, PV compensates the energy deficiency of hydropower via its generated electricity.

Based on the analysis above, the complementarity of hydropower and PV is bidirectional. Therefore, the principle of complementary hydro/PV operation can be observed from the perspectives of PV and hydropower.

The superior adjusting performance of hydropower units is used to compensate the variable output of PV in real time. Namely, hydropower reduces its output with increases in the PV output, and water originally used to generate electricity can be kept in reservoirs. When the PV output decreases, hydropower instantly increases its output to support PV. Superposed by the compensatory output of hydropower, the intermittent and random output of PV becomes a relatively constant value, and stable and reliable PV electricity is attained. A constant output of PV is desirable because when solar, wind, or other renewable resources are exploited at a large scale, the local electricity market may not be able to accommodate all of the newly established RES power, and a feasible option is to deliver the electricity generated by RESs to remote load centers, which could be thousands of miles away. However, more stable or constant power output is preferable for long-distance transmission to avoid the wide-range and substantial changes in power flow and voltage fluctuation. In the receiving-end power system, the constant RES power will be injected as the base load. For instance, in Gansu Province where large amounts of wind and solar energy are located, the installed capacity of wind power reached 5.16 GW by the end of 2010; however, the maximum load of the entire province was only 9.8 GW. A 10 GW wind power base is under construction in Jiuquan City, Gansu Province. To consume the massive wind power and ensure the safety of the power system, construction of a ±800 kV high-voltage direct current (HVDC) transmission line began in 2015, and wind power bundled with thermal power will be directly transmitted to Hunan Province, which is 2400 km away from Jiuquan. In China, there is a reverse distribution of energy resources and load demands, which means that fossil, hydro, solar, and wind energy resources primarily concentrate in western and northern China, whereas the eastern portion of China is only the load center. Therefore, long-distance and high-capacity transmission will be an indispensable solution for accommodating large amounts of utility-scale RES power, and relatively constant transmission power is needed. However, when PV power is integrated into the local power system, hydropower must follow the variations of load demands and participate in satisfying the peak load after compensating for PV.

Therefore, the novel hybrid power source coordinating utility-scale PV and hydropower in the neighboring area can operate flexibly in practice. The complementary power is suitable for trans-provincial transmission and can be consumed locally. In the context of the rapid expansion of utility-scale RESs, a qualified and stable power supply that is particularly suitable for long-distance transmission can be provided by the coordinated hydro/PV power source. If PV power is interconnected with the local electricity market and the volume of reservoir is sufficiently large, the hybrid power source can follow the fluctuations in load demands and play a role in peak load regulation.

B. Virtual hydropower

For the Longyangxia complementary hydro/PV project, the electricity generated by the 320 MW PV plant is transmitted to the Longyangxia hydropower plant through 330 kV high-voltage transmission lines and then fed into the power system after being bundled with electricity produced from the hydropower plant. From the perspective of the power system, the 320 MW PV plant can be treated as a newly installed unit of a hydropower plant, which achieves the production schedule with the other four hydropower units.

In general, when an RES power plant is coordinated with a hydropower plant, we regard it as an additional virtual unit of the hydropower plant. Furthermore, if a complementary operation mode can be achieved between RES power and hydropower and the electricity fed into the power system is bundled together, then RES power is referred to as virtual hydropower.

Virtual hydropower has the following advantages over co-optimizing the entire system generation together to balance the load demand:

- When firmed up by hydropower, the intermittent and random power output of RESs is stabilized, and highly variable RESs are converted into superior electricity. The complementary operation will motivate the full utilization of RESs and increase the profits of RES power producers considerably.
- Once the compensation is implemented, the power system can reduce the spinning reserves, which were originally scheduled to accommodate the variability and are numerically equal to the installed capacity of the RESs. Operation risk is shifted from the power system to the RESs and hydropower owners. Thus, the operation cost of the power system will decrease accordingly, and more RES power capacity can be integrated into the system. For the 320 MW PV power plant coordinated with hydropower, if the price of spinning reserves (200 RMB/MW h)[13] and the duration of sunshine daily (12 h) are considered, the operation expense of power system may cut down by 280 320 000 RMB annually.
- Electricity generated by virtual hydropower can satisfy the load demand instead of fossil fuels, thus reducing GHG emission. For instance, the mean annual energy production of the 320 MW PV plant is projected to be 482 983 000 kW h. In 2014, the standard coal consumption per kW h of China's thermal power industry is 318 g/kW h. Thus, when PV electricity is fed into the system, approximately 154 000 ton of coal can be saved, and CO_2, SO_2, and NO_x emissions will, respectively, decrease by 383 500 ton, 4620 ton, and 2310 ton. Additional reductions in GHG emissions can be obtained because virtual hydropower does not require spinning reserves to serve as backup.
- Standalone RES power tends to widen the gap between the peak load and valley load of a power system. However, when working in the complementary mode, RESs and hydropower are dispatched by the system as an integrated power source, and RESs are able to help in satisfying the peak load via their real-time output. Furthermore, supported by the electricity generated by RESs, hydropower can allocate hydro energy in a flexible manner and behave more competitively in peak load regulation.

III. ANALYSIS OF THE CAPACITY OF HYDROPOWER TO COMPENSATE FOR PV

A. Description of hydro/PV short-term scheduling

In a power system, short-term scheduling is a power dispatching problem whose operation period is one or several days and whose operation interval is, for example, 15, 30, or 60 min.

Hydro/PV short-term scheduling can be formulated as follows: based on the water balance, various problems can be investigated, such as the balance of electric power and energy during one day or one week, the rational distribution of the load between hydropower and PV, the capacity of hydropower to compensate for PV, and the ability of hydro/PV power to regulate the peak load.

B. Derivation of the formula of hydropower's compensation for PV

In daily generation scheduling, complementary hydro/PV operation should achieve three goals. First, the daily outflow of the hydropower plant must meet the minimum level proposed by watershed management departments. Second, superposed by the complementary output of hydropower, the output of PV should reach a relatively constant level throughout the day and ensure that electricity via PV obtains access to the system to the fullest extent. Third, PV and hydropower must satisfy the production schedule dispatched by the system, namely, realizing the balance of electric power and energy.

Several technical terms of hydropower must be explained before deriving the formula.

Forced output: Due to irrigation, the water supply, shipping, and other downstream demands, a reservoir must satisfy a constraint on the minimum discharge. The output corresponding to the minimum discharge is called forced output and is denoted by N_q.

Expected output: The maximum output of a hydraulic turbine varies from different hydraulic heads. The expected output is the smaller of the maximum output of hydraulic turbine and the rated capacity of the generator and is denoted as N_{yu}.

Adjustable output: Aside from forced output, a range $[N_q, N_{yu}]$ in which the output of a hydropower plant lies is defined as the adjustable output.

Maximum adjustable output: The maximum adjustable output is the upper limit of the adjustable output and is denoted by N_T''.

Forced energy: Forced energy is the energy production accumulated by forced output during one day and is calculated by $E_q = N_q \times 24$.

Adjustable energy: Adjustable energy is hydro energy that a hydropower plant can utilize to compensate for PV and satisfy the peak load of the power system. Adjustable energy can be calculated by $E_S = (N_P - N_q) \times 24$, where N_P is the mean daily output of a hydropower plant.

From the perspective of a hydropower plant, its daily adjustable energy is divided into two parts, as illustrated in Fig. 3. The first part is used to compensate for PV and is denoted by E_1. The second part is used to satisfy the peak load and is denoted by E_2.

When the daily energy production of a PV power plant (E_G), the daily maximum output of PV (G), the daily gross energy production of the hydro/PV power source (E_Z), and the peak load of the generation schedule (S) are known, the capacity of hydropower to compensate for PV can be evaluated as follows:

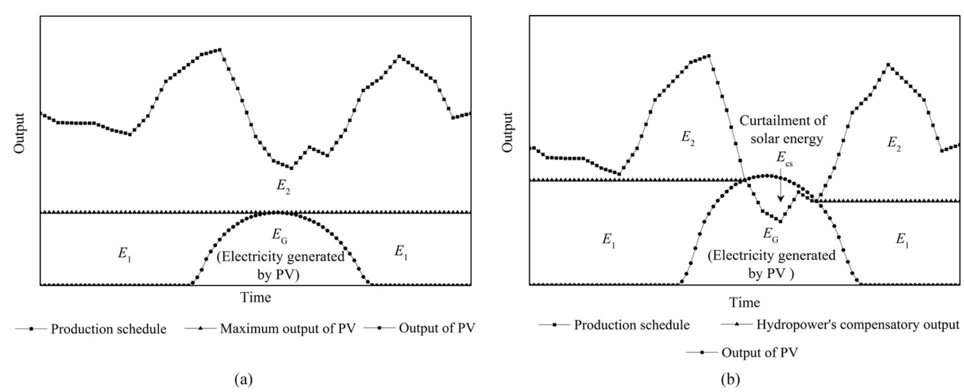

FIG. 3. Schematic of the dispatch of hydropower's adjustable energy. In (a), the output of PV is always smaller than the load of generation schedule, and in (b), the output of PV is occasionally larger than the corresponding load.

(1) If the output of PV is always smaller than the load of generation schedule, then the daily energy production of a PV plant (E_G) can be expressed by

$$E_G = \sum_{i=1}^{24} E_{Gi}, \tag{1}$$

where E_{Gi} is the energy production of PV in the i-th hour.
The adjustable energy of hydropower (E_S) can be calculated as

$$E_S = (N_P - N_q) \times 24. \tag{2}$$

The compensatory hydro energy required by PV (E_1*) is

$$E_1^* = E_{hb} - E_G = 24 \times G - \sum_{i=1}^{24} E_{Gi}. \tag{3}$$

The hydro energy needed for peak load regulation (E_2*) is expressed as

$$E_2^* = E_Z - E_{hb} = E_Z - 24 \times G. \tag{4}$$

According to the relationship between the maximum adjustable output N''_T and the peak load of the generation schedule S, three scenarios are discussed:

(i) When $N''_T \geq S$, the PV output process of a sunny day is considered, and the daily insolation duration is H, then
  (a) If $E_S \geq E_1^* + E_2^*$, hydropower can simultaneously compensate for PV and satisfy the peak load, as shown in Fig. 4 by N_{P1}. In this figure, different N_P values indicate different levels of adjustable energy E_S from hydropower.
  (b) If $E_1^* \leq E_S < E_1^* + E_2^*$, hydropower is able to compensate for PV, but it cannot completely regulate the peak load, as denoted by N_{P2} in Fig. 4. The deficiency of hydro energy needed to regulate the peak load is calculated as follows:

$$\Delta E_2 = E_2^* - E_2' = E_2^* - (E_S - E_1^*) = E_Z - 24 \times (N_{P2} - N_q) - \sum_{i=1}^{24} E_{Gi}, \tag{5}$$

  where E_2' is hydropower's surplus energy after compensating for PV.
  (c) If $E_S < E_1^*$, hydropower cannot compensate PV by itself; thus, other power generation sources are needed, as shown by N_{P3} in Fig. 4. Based on the output curve of

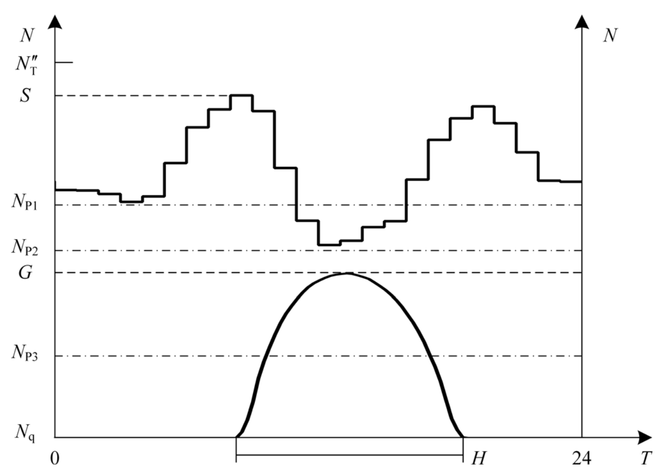

FIG. 4. Schematic of the compensation calculation when the maximum adjustable output is larger than the peak load of the generation schedule.

PV and E_S, the maximum output of PV (G') that hydropower is able to compensate for can be computed by the iteration method. Then, the electricity generated by PV that hydropower fails to compensate for is calculated as

$$\Delta E_1 = E_G - (24 \times G' - E_S) = \sum_{i=1}^{24} E_{Gi} - 24 \times (G' - N_{P3} + N_q). \tag{6}$$

When the PV output curves of other weather conditions are considered, the calculation methods formulated above are also applicable.

(ii) When $G \leq N''_T < S$ (shown in Fig. 5), hydropower is unable to regulate the peak load assigned by the power system and can only compensate for PV.
  (a) If $E_S \geq E_1^*$, hydropower is capable of compensating for PV.
  (b) If $E_S < E_1^*$, hydropower cannot compensate for PV by itself, and other power generation sources must be used, as shown by N_{P4} in Fig. 5. Once the maximum output of PV G' that hydropower can compensate for is determined by the iteration method, the electricity generated by PV that hydropower fails to compensate for is calculated by

$$\Delta E_1 = E_G - (24 \times G' - E_S) = \sum_{i=1}^{24} E_{Gi} - 24 \times (G' - N_{P4} + N_q).$$

(iii) When $N''_T < G$ (shown in Fig. 6), hydropower fails to compensate for PV merely by itself, and other power generation is needed. The maximum PV output (G') that hydropower can compensate for can be attained through an iterative procedure.
Furthermore, if $G' < N''_T$, electricity generated by PV that hydropower cannot compensate for is expressed as

$$\Delta E_1 = E_G - (24 \times G' - E_S) = \sum_{i=1}^{24} E_{Gi} - 24 \times (G' - N_{P5} + N_q).$$

However, if $G' \geq N''_T$, then G' is equal to N''_T. Hydro energy utilized to generated electricity E'_S is less than adjustable energy E_S. Therefore, electricity generated by PV that hydropower fails to compensate for is expressed as

$$\Delta E_1 = E_G - (24 \times G' - E'_S) = E_G - (24 \times N''_T - E'_S). \tag{7}$$

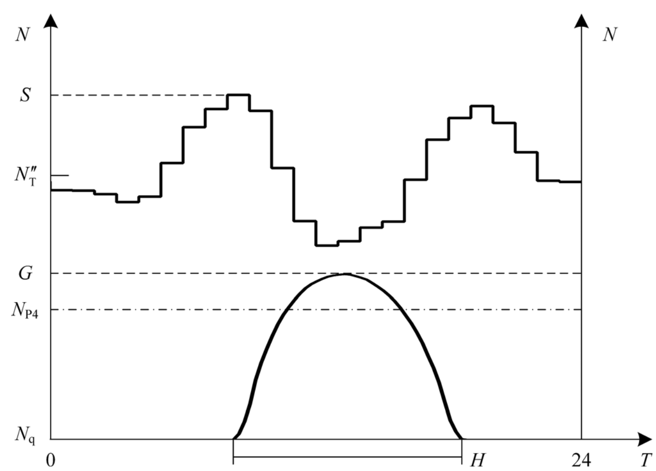

FIG. 5. Schematic of the compensation calculation when the maximum adjustable output is smaller than the peak load of the generation schedule and larger than the daily maximum output of PV.

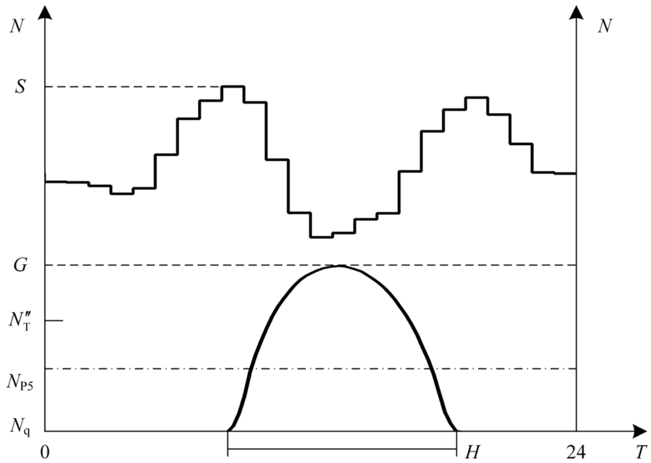

FIG. 6. Schematic of the compensation calculation when the maximum adjustable output is smaller than the daily maximum output of PV.

(2) If the output of PV is larger than the corresponding load of generation schedule in some operation intervals and there is no other power generation engaging in the compensation, the solar energy will inevitably be curtailed. The curtailed solar energy E_{cs} is represented by

$$E_{cs} = \sum_{i=1}^{m} \Delta N_{Gi} \cdot \Delta t, \tag{8}$$

where m denotes the total operation intervals in which the PV output is larger than the load dispatched by the power system; $\triangle N_{Gi}$ is the difference between the output and load in the same operation interval, where $\triangle t$ denotes the operation interval.

As shown in Fig. 3(b), hydropower compensates for PV in two periods, i.e., in the morning and in the afternoon, and the PV output that must be compensated for during these two periods is G_1 and G_2, respectively. If compensatory hydro energy in the morning is E^*_{1m} and its compensatory hydro energy in the afternoon is E^*_{2m}, the hydro energy needed to compensate PV throughout the day (E^*_1) can be calculated as follows:

$$E^*_1 = E^*_{1m} + E^*_{1a}. \tag{9}$$

The hydro energy needed in peak load regulation E^*_2 is expressed as

$$E^*_2 = E_Z - E_{hb} = E_Z - [(E_G - E_{cs}) + E^*_1]. \tag{10}$$

According to the relationship between the maximum adjustable output N''_T and peak load of the generation schedule S, two scenarios are discussed:

(i) When $N''_T \geq S$, PV's output process of a sunny day is considered and the daily insolation duration is H, then

(a) If $E_S \geq E^*_1 + E^*_2$, hydropower can simultaneously compensate for PV and satisfy the peak load, as shown by N_{P6} in Fig. 7.

(b) If $E^*_1 \leq E_S < E^*_1 + E^*_2$, hydropower is able to compensate for PV but cannot regulate peak load, as shown by N_{P7} in Fig. 7. The deficiency of hydro energy needed in the peak load regulation is computed as follows:

$$\Delta E_2 = E^*_2 - E'_2 = E^*_2 - (E_S - E^*_1) = E_Z - E_G + E_{cs} - 24 \times (N_{P7} - N_q), \tag{11}$$

where E'_2 is the surplus hydro energy after compensating for PV.

(c) If $E_S < E^*_1$, hydropower cannot compensate for PV by itself, and other power generation sources are needed, as shown by N_{P8} in Fig. 7. Based on the output curve

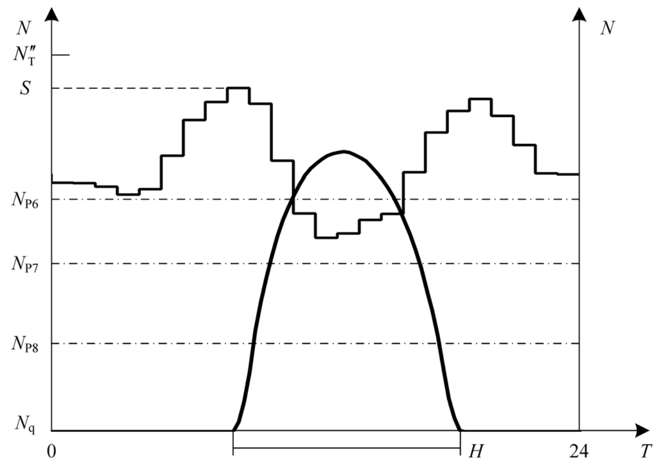

FIG. 7. Schematic of the compensation calculation when the output of PV is occasionally larger than the corresponding load of generation schedule.

of PV and adjustable energy of hydropower, the maximum output of PV (G') that hydropower is able to compensate for can be obtained via the iteration method. Then, the electricity generated by PV that hydropower fails to compensate for is calculated as

$$\Delta E_1 = E_G - (24 \times G' - E_S) = E_G - 24 \times (G' - N_{P8} + N_q).$$

When other weather conditions are considered, the previous analysis can act as a reference.

(ii) The calculation method outlined above can also be applied when $G \leq N'_T < S$ or $N''_T < G$.

C. Curtailment of solar energy and water

If the water elevation of a reservoir has reached its highest limited elevation preset and the inflow of the reservoir exceeds the maximum discharge of hydraulic turbines, the outflow will be at least not less than the inflow to ensure the safety of the dam. Then, a portion of water will flow downstream from spillways rather than pass through hydraulic turbines to generate electricity, and this phenomenon is called water curtailment. Similar to the curtailment of solar energy, water curtailment is a critical index to evaluate the economics of hydropower. Hydropower and PV both serve as the basic components of a hydro/PV power source; thus, causes of water curtailment and solar curtailment are briefly discussed here.

1. Curtailment in the dry season

When the large power output of PV encounters small load demands in the generation schedule, hydropower units must reduce their output and may operate in small opening operation conditions where the vibration prevails. However, once the stability and safety of units are attached more attention, PV will curtail a portion of the solar energy to decrease its output, or the hydro/PV power source will request more load from the power system.

In the dry season, the electricity generated by hydropower is limited by the relatively less inflow of the reservoir, and the production schedule assigned by the power system is smaller than in the wet season. Once the output of PV is larger than the corresponding load demand of the production schedule, other power generation sources must reduce their output so that the system can accommodate all of the electricity generated by PV. If compensation of other power options is not available, solar energy curtailment will inevitably occur.

2. Curtailment in the flood season

In the flood season, the water elevation is strictly restricted by the limited elevation for flood control. In this period, hydropower typically operates at full capacity, and its output serves as the base load of power system. Thermal power is employed to satisfy the peak load. Once thermal power is unable to cover the peak load completely, hydropower will curtail a portion of the water to participate in peak load regulation. Moreover, in the flood season, hydropower is incapable of compensating for PV, and thus, other power generation sources are needed. Once the system fails to accommodate the electricity generated via PV, a portion of solar energy will be curtailed or hydropower will curtail the water to reduce the output and make room for PV.

D. Capacity of the hydro/PV power source to satisfy the peak load

Due to the instability and variability of solar radiation intensity, PV output is intermittent and random. As a result, PV is considered to provide an unstable electricity supply instead of substituting a certain amount of the generation capacity. In peak load regulation, PV power is regarded as an unreliable power source that does not contribute to satisfying the peak load and also occupies spinning reserves that are equivalent to the installed capacity of PV.

Compared with PV, hydropower provides a highly reliable and adjustable output. However, its energy production is influenced by the water storage capacity of reservoirs, natural runoff, and comprehensive utilization of water resources. In the dry season, the hydropower plant is often unable to fully utilize its installed capacity to satisfy the peak load due to the limited inflow.

If complementary hydro/PV operation is implemented, hydropower will reduce its output when solar energy is available, and the saved hydro energy can be used in peak hours. Therefore, the capacity to satisfy the peak load will be improved based on the reliable power capacity provided by hydropower and the supplementary electricity generated by PV.

IV. CASE STUDY

In the Yellow River, the Longyangxia reservoir is the only multi-year regulating storage reservoir whose storage cycle (the water elevation rises from the minimum operating elevation to the normal storage elevation and then decreases to the minimum operating elevation again) lasts for several years. The installed capacity of the Longyangxia hydropower plant is 1280 MW, and its mean annual power generation is 5.94 GW h. Longyangxia PV power plant is located 31 miles east of the hydropower plant. The installed capacity is 320 MWp, and its mean annual power generation is approximately 0.48 GW h. The PV output curves in sunny, cloudy, and rainy days as well as the typical output curve of hydropower are plotted in Fig. 8. Based on the typical curves above, the total output curves of hydro/PV power source can be attained via a backstepping method and a simulation optimization approach.

The calculation results shown in Fig. 8 indicate that there is no solar energy curtailment in PV plant, which means that electricity generated by PV has been completely accommodated by

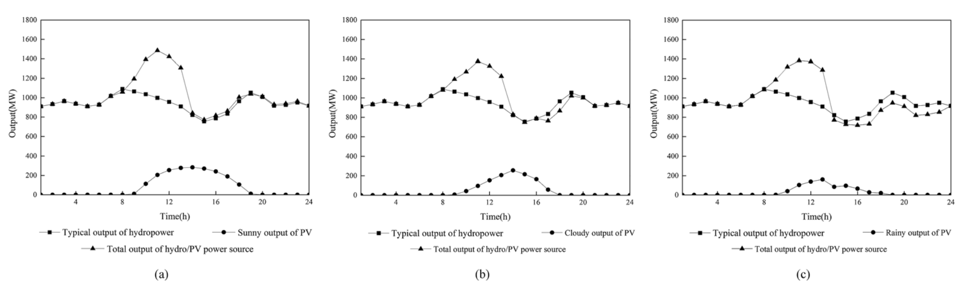

FIG. 8. Output curves of the hydro/solar power source under different weather conditions. (a) Sunny day; (b) cloudy day; and (c) rainy day.

the power system. Before complementary hydro/PV operation, the maximum capacity of hydropower for satisfying the peak load was equal to its installed capacity, i.e., 1280 MW. However, when the complementary operation is implemented, the hydro/PV power source reaches its maximum output at approximately 11:00. Compared with the maximum capacity for satisfying the peak load before the compensation, the corresponding maximum capacity in sunny, cloudy, and rainy days has increased by 18%, 9%, and 5%, respectively. During other periods, the output of the hydro/PV power source is consistent with the trends of hydropower's typical output. However, if no solar energy is available, the maximum capacity for covering the peak load is still 1280 MW. To conclude, the curtailment of solar energy can be effectively prevented by complementary hydro/PV operation; the hydro/PV power source is better able to satisfy the peak load than a standalone hydropower plant and therefore enhances the system's ability to regulate the peak load.

V. CONCLUSIONS

The world's largest hydro/PV power source, namely, the Longyangxia complementary hydro/PV project, has been successfully implemented. It provides a novel operation mode for utility-scale PV power generation and validates the feasibility and reliability of complementary hydro/PV operation. Despite its successful operation, the new operation mode still lacks theoretical and methodological support. Therefore, taking the Longyangxia project as an example, this paper has preliminarily explored the theories and methods of complementary hydro/PV operation in short-term scheduling. The following conclusions can be drawn:

(1) The principle of hydro/PV complementary operation has been established by analyzing the characteristics of hydropower and PV. Namely, via the first-stage compensation for the sawtooth-shaped output curve of PV and the second-stage compensation for the intermittent and random output of PV, hydropower can compensate for the unstable output of PV through its rapidly adjustable output in short-term scheduling. Conversely, PV is able to compensate for the hydro energy deficiency of hydropower during mid- to long-term scheduling and satisfying the peak load.

(2) The concept of virtual hydropower has been proposed. When an RES power plant is coordinated with a hydropower plant, we regard it as an additional virtual unit of the hydropower plant. Furthermore, if a complementary operation mode can be achieved between RES power and hydropower and their electricity fed into the power system is bundled together, then RES power is referred to as virtual hydropower.

(3) The capacity of hydropower to compensate for PV has been analyzed in short-term scheduling. Formulas for the compensation of PV via hydropower have been derived, and scenarios of the curtailment of solar energy and water as well as their causes have been discussed.

(4) The capacity of the hydro/PV power source to satisfy the peak load has been calculated. The results show that complementary hydro/PV operation is able to effectively prevent and reduce the curtailment of solar energy, and it is better able to satisfy the peak load than a standalone hydropower plant.

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