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Coordinated Optimization of Wind Energy and Other Sources: Objective and Examples

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Abstract: Wind power is inherently variable and intermittent, and thus it brings great challenges to the operation of power systems. Noting that there have been considerable dispatchable sources in power systems, the coordination of wind power generation with the dispatchable sources provides the possibility to overcome the drawbacks of wind power. In this paper, the choice of coordination objective is discussed, or the output of wind power or the combine system should satisfy the requirements of the whole power systems. Based on the above principle, two examples are given. Firstly, the coordinated optimal control of wind-storage system is proposed. The objective of the coordinated control is to meet the ramp rate limit of grid code. Secondly, the coordinated optimal dispatch of wind-thermal-pumped hydro system is proposed. The objective of the coordinated dispatch is to make the output of the combined system more correlated with the system load. The optimal model and algorithm of the two examples are designed. The simulation results also validate the effectiveness of the proposed methods.

1. INTRODUCTION

Recently, wind energy is rapidly developing in China and around the world. Wind power is inherently variable and intermittent, and thus it brings great challenges to the operation of power systems. Meanwhile, there have been considerable controllable and dispatchable sources in power systems, such as conventional generation, energy storage and demand response. The coordination of wind power generation with these dispatchable sources provides the possibility to overcome the drawbacks of wind energy.

Many studies have been done to cope with the variations of wind power. Teleke et al. (2009) presents a wind-battery energy storage system whose output is controlled as much smoothing as possible. Saejia et al. (2011) combines superconducting magnetic energy storage with wind farm to minimize the variance of output power. Greenblatt et al. (2007) proposes a compressed air energy storage to transform wind energy from an intermittent source into a base-load electricity source. In a deregulated electricity market, wind power with other sources can be considered as merchant units, which maximize their profits subject to technical constraints (Sioshansi, *et al.*, 2010; Garcia, et al., 2008).

The focus of this article is to discuss the choice of the control objective in the field of coordinating wind energy and other sources. Although much research has been devoted to the wind-source coordination, rather less discussion has been focused on whether their control objectives are necessary and appropriate. For example, some researches tried to smooth wind power output as much as possible. However, for integrated wind farm, it is neither necessary nor desirable to smooth wind power output too much.

The authors in this paper believe that the control objective should match with the operation requirements of power systems. The main contribution of this article is to establish coordination operation strategies for wind-source based on the power system requirements. In this paper, two separate examples of the coordinated operation are given as following.

1) Smoothing wind variations: Many grid codes have set limits for wind power ramping. Therefore, it is a must to mitigate the variations of wind power output to fulfill this requirement. Various methods have been explored to control the ramp rate within the grid code limits with options such as power electronics control (Miller, *et al.*, 2010), wind curtailment (Vigueras, *et al.*, 2009) and wind turbine shutdown (Kim, *et al.*, 2012). However, little has been done to explore the optimal control of wind and other sources to fulfill the ramp rate requirement. In this paper, coordinated control of wind-storage system to meet ramp rate limits of grid code is studied.

2) Matching load variations: The drastic variability of wind farms makes it harder for system operators to make economic dispatch. Existing researches have explored how to use complementary sources to benefit dispatch by providing base-load, peak shaving and time shifting. In this paper, the authors note that the power system operators would rather to integrate wind power which is more correlated with the system demand, rather than the opposite. Based on day-ahead wind power forecast, a coordinated dispatch method of wind power with other sources is proposed to make the output of the combined system more correlated with the system demand. This method is especially meaningful for a regulated power system, such as the grid of China.

2. COORDINATED CONTROL TO MEET RAMP RATE LIMITS OF GRID CODE

2.1 Ramp Rate Limit of Different Grid

Large ramps of wind power outputs bring difficulty for power system control. Recently, some countries and electric power companies have announced technical requirements for integrated wind farms, and the ramp rate is required to be mitigated within different restrictions. Table 1 illustrates the ramp rate limits of integrated wind power in world-wide grid codes.

Table 1. Ramp rate limit of grid codes

ISO/TSO	Ramp Rate Limit /install capacity (ic.)		
Eltra&Elkraft	1 min<5% ic.		
ERCOT	1 min<10% ic.		
ESBNG	ic.<100 MW	ic.<200 MW	ic.>200 MW
	1 min< 5% ic.	1 min< 4% ic.	1 min< 2% ic.
CEPRI (China)	ic.<30 MW	ic.<200 MW	ic.>200 MW
	1 min< 3 MW	1 min< ic. / 10	1 min< 15 MW
	10min< 10 MW	10min< ic. /3	10min< 50 MW

In the following of this section, an optimization control of wind-energy storage system will be proposed to mitigate the wind power variations to meet the ramp rate limit of grid codes. The optimization method provides more precise control, which requires much less capacity of energy storage. Considering wind power forecast errors can be decreased with shorter forecast period, a rolling optimization control model is established based on the ultra-short-term wind power forecast.

2.2 Mathematical Formulation

The objective is to maximize total income of the wind-storage system. The objective function given by (1) consists of four parts: (a). Income from power output to the grid. (b). Operational cost of energy storage system. (c). Cost of curtailing wind power. (d). Penalty for violating the ramp rate limit of the grid codes.

$$\text{Max} \sum_{k=1}^{K} \left[\pi_k^g P_k^g - \pi_s \times \left| P_k^s \right| - \pi_{curt} \times \left| P_k^{curt} \right| - M \cdot \left| P_k^p \right| \right] \quad (1)$$

where, π_k^g is the electricity price; P_k^g is the output of wind-storage combined system; M is a very large number; P_k^p is the power penalized for violating the ramp rate limit of the grid codes; π_s is the operational cost of energy storage system; P_k^s is the power charged (negative) and discharged (positive) of energy storage system; π_{curt} is the wind curtailing cost; P_k^{curt} is the power curtailed.

This optimization problem is subject to the followings:

$$P_k^g = P_k^s + P_k^w - P_k^{curt} \quad (2)$$

$$P_{\min}^s \le P_k^s \le P_{\max}^s \quad (3)$$

$$SOC_{\min} \le SOC_k \le SOC_{\max} \quad (4)$$

$$SOC_{k+1} = SOC_k - P_k^s \Delta T / J_s \times 100\% \quad (5)$$

$$P_k^p = \frac{1}{2}\left[\operatorname{sgn}\left(P_k^{ramp\_1\min} - P_{1\min} \cdot h \right) + 1 \right] \times \left(P_k^{ramp\_1\min} - P_{1\min} \cdot h \right) + \frac{1}{2}\left[\operatorname{sgn}\left(P_k^{ramp\_10\min} - P_{10\min} \cdot h \right) + 1 \right] \times \left(P_k^{ramp\_10\min} - P_{10\min} \cdot h \right) \quad (6)$$

where, k is the index of 10 seconds periods for 20 minutes and K=120; i is index of 10 seconds periods; for 1 minute, I1min=6 , for 10 minutes, I10min=10. P_k^w is the wind power forecast; $P_{\min}^s$ and $P_{\max}^s$ are the minimal and maximal power of energy storage, respectively; SOC_k is the state of charge of the energy storage; $SOC_{\min}$ and $SOC_{\max}$ are the minimal and maximal state of charge, respectively; J_s is the rated capacity of energy storage; $P_{1\min}$ and $P_{10\min}$ are the ramp rate limits over 1 minute and 10 minutes of grid codes, respectively; $P_k^{ramp\_1\min}$ and $P_k^{ramp\_10\min}$ are the maximal ramp rate over 1 minute and 10 minutes; h is the safety margin coefficient.

The power balance equation of wind-storage system is shown in (2). The operational limits of the energy storage are shown from (3) to (5). The power violating the ramp rate limits is shown in (6).

Today, there is no standard way in which the ramp rate is defined mathematically. The typical definitions of ramp rate are shown as (7) and (8).

$$\left| P(t+T) - P(t) \right| \quad (7)$$

$$\max P\left[t, t+T\right] - \min P\left[t, t+T\right] \quad (8)$$

However, the definitions above are not perfect in rolling optimization control. The definition of (7) focuses only on the two endpoints of the interval being considered, and may miss the maximal ramp if it occurs between the two endpoints. For the data of the previous control horizon is utilized in the rolling optimization control, the definition of (8) may lead to control mistakes if there is any control mistake in the previous control horizon, it may lead to control mistake in the current control horizon.In this paper, we develop a robust metric to define the ramp rate especially for rolling optimization control, as shown in (9).

$$\max \left\{ \left| P(t) - P(t-i) \right| \right\}, i = 1, 2, ..., T \quad (9)$$

Equation (10) and (11) define the ramp rate over 1 minute and 10 minutes, respectively.

$$P_k^{ramp\_1\min} = \max\{\left|P_k^g - P_{k-i}^g\right|\},\ i = 1,2,...,6 \quad (10)$$

$$P_k^{ramp\_10\min} = \max\{\left|P_k^g - P_{k-i}^g\right|\},\ i = 1,2,...,60 \quad (11)$$

2.3 Case Study

The testing data are based on an actual wind-solar-storage demonstration project in China. The installed capacity of wind farm is 100MW. According to the Grid Code in China, the ramp rate limits of this wind farm are 10MW every 1 minute and 33.3MW every 10 minutes. Other parameters are given in Table 2. The initial SOC is set as 50%.

Table 2. Parameters of wind-storage system

$P_{\min}^s$	$P_{\max}^s$	$SOC_{\min}$	$SOC_{\max}$
-10	10	0.2	0.8
J_s	π_k^g	π_{curt}	π_s
10	600	300	800

The wind power forecast is shown in Fig. 1 by curve. The bar graph shows whether the ramp rate limits are violated. "1" means the ramp rate limit over 1 minute is violated, "2" means the ramp rate limit over 10 minutes are violated, "3" means the ramp rate limits over 1 minute and 10 minutes are violated. As shown in Fig. 1, the ramp rate limits are violated many times without any control.

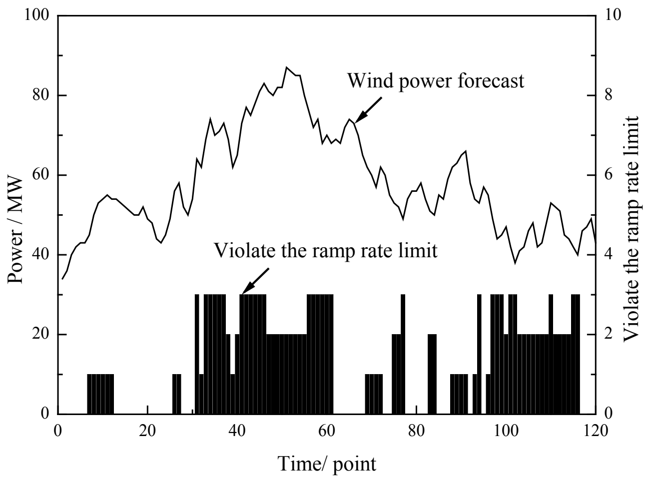

Fig. 1. Wind power forecast and violation of the ramp rate limit

The optimization results are shown in Fig. 2-3. It is obvious that the bar graph is zero, which means neither of the ramp rate limits over 1 minute nor 10 minutes are violated. The energy storage is charged at peak wind, and discharged at other time. It should be noted that around point 50, the energy storage is not charging at the maximal power while the wind is curtailed. It is because the cost of energy storage is higher than that of the wind curtailment.

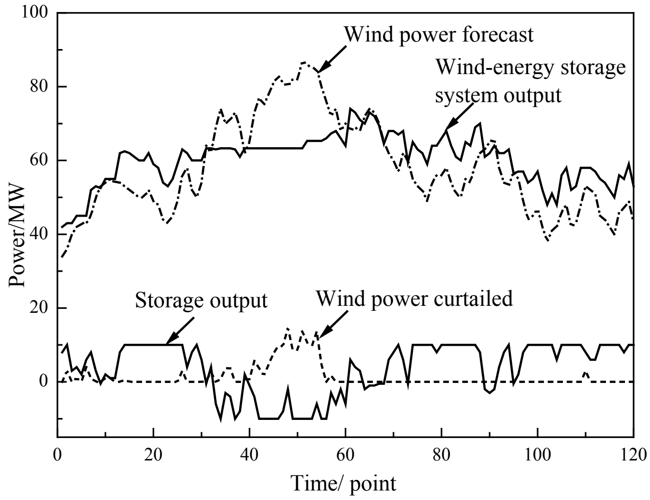

Fig. 2. Optimized power(initial SOC=50%)

3. COORDINATED DISPATCH TO BE CORRELATED WITH SYSTEM LOAD

3.1 Correlated With Load

For day-ahead dispatch, the variability of wind farms may bring much difficulty to the operation of conventional units. In this section, we notes that power system operators would rather to integrate wind power whose output is more correlated with the system demand, rather than the opposite. Based on day-ahead wind power forecast, a coordinated dispatch of wind-thermal-pumped hydro system is proposed, in order to make the output of the combined system more correlated with the system demand. Fig. 3 illustrates the coordination strategy.

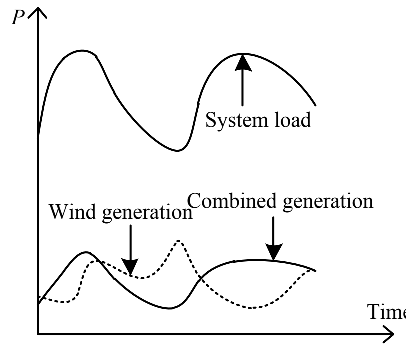

Fig. 3. Coordination strategy

Typically, the Pearson correlation coefficient is used to analyze the linear correlation between different sources. However, the sample correlation coefficient does only represent the linear correlation, but not shows the quantity relationship of the variables. As shown in Fig. 5, the Pearson correlation coefficient between load and G1, G2, G3 are all the same (equal to 1.0). However, it is not reasonable to treat G1, G2 and G3 as the same. For example, while the load is rapidly rising at around 8 a.m., the rise in G2/G3 is much larger than that in G1. Thus, compared with G1, G2 and G3 contribute more to following the trend of load.

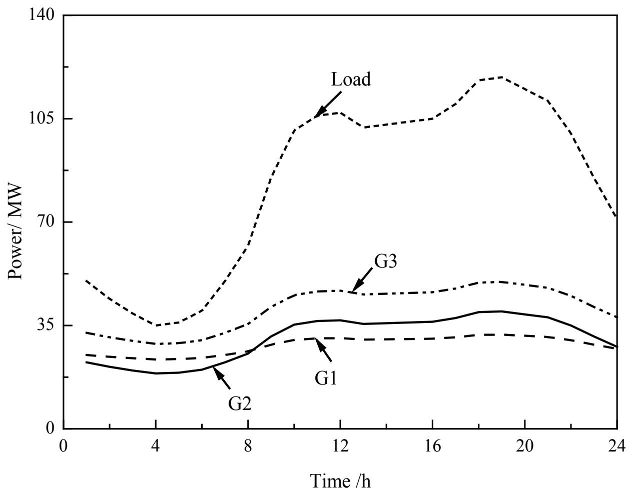

Fig. 4. Load and generation G1~G3.

In this paper, a different correlation coefficient is proposed to overcome the disadvantages of the Pearson correlation coefficient. The proposed correlation coefficient is the Euclidean distance between the deltas of two variables. The formula is:

$$r(x,y)=\sqrt{\frac{1}{N-1}\sum_{n=1}^{N-1}\left(R_X(n)-R_Y(n)\right)^2} \tag{12}$$

$$R_X(n)=X(n+1)-X(n) \tag{13}$$

The proposed correlation coefficient could reflect the quantity relationship of the combined output and the system load. The proposed correlation coefficient equals to 0 in the case of exactly correlated. The closer the proposed coefficient is to 0, the stronger the correlation between the variables.

3.2 Mathematical Formulation

This problem is formulated as a multi-objective optimization problem. Firstly, the proposed correlation coefficient of system load and the wind-thermal-pumped hydro generation is minimized. Secondly, the economic benefit of the combined system is required to maximum.

$$\min r(x,y)=\sqrt{\frac{1}{K-1}\sum_{k=1}^{K-1}\left(R_k^l-R_k^g\right)^2} \tag{14}$$

$$\max\sum_k\left[\pi_k^g\left(P_k^w+P_k^{thm}+P_k^{hg}-P_k^{hp}\right)-C_k^{thm}-\pi_{hu}n_k^{hu}-\pi_{hd}n_k^{hd}\right] \tag{15}$$

The R_k^g and P_k^l are defined by:

$$R_k^l=P_{k+1}^l-P_k^l \quad \forall k\in\{1,2,...,K-1\} \tag{16}$$

$$R_k^g=P_{k+1}^w-P_k^w+P_{k+1}^{thm}-P_k^{thm}+P_{k+1}^{hg}-P_k^{hg}-P_{k+1}^{hp}+P_k^{hp} \tag{17}$$

where, k is the index of 10 seconds periods for one day and K=24; R_k^l is the step change of system load; R_k^g is the step change of combined generation; π_k^g is the electricity price; P_k^w is the actual wind power output, which is presumed to be accurately predicted; $P_{l,k}$ is the system load; P_k^{thm} is the thermal unit output; P_k^{hg} and P_k^{hp} are generating and pumping power of pumped-hydro generation, respectively; $C_{thm,k}$ is the cost of thermal generation; π_{hu} and π_{hd} are startup and shutdown cost of pumped hydro for pumping, respectively; n_k^{hu} and n_k^{hd} are number of pumping units started up and shut down, respectively.

This optimization problem is subject to the followings:

$$P_{\min}^{thm}\cdot t_k^{thm}\le P_k^{thm}\le P_{\max}^{thm} \ \forall k\in K \tag{18}$$

$$-\Delta P_{\min}^{thm}\le P_{k+1}^{thm}-P_k^{thm}\le\Delta P_{\max}^{thm} \quad \forall k\in K \tag{19}$$

$$t_k^{thm}\ge P_k^{thm}\big/P_{\max}^{thm} \tag{20}$$

$$V_{\min}^{hu}\le V_k^{hu}\le V_{\max}^{hu} \quad \forall k\in K \tag{21}$$

$$V_{\min}^{hd}\le V_k^{hd}\le V_{\max}^{hd} \quad \forall k\in K \tag{22}$$

$$V_k^{hu}=V_{k-1}^{hu}+up(P_k^{hp},H_p)-down(P_k^{hg},H_p) \quad \forall k\in K \tag{23}$$

$$V_k^{hu}=V_{k-1}^{hu}-up(P_k^{hp},H_k)+down(P_k^{hg},H_k) \quad \forall k\in K \tag{24}$$

$$\delta_{\min}^{hu}\le V_{24}^{hu}-V_1^{hu}\le\delta_{\max}^{hu} \tag{25}$$

$$\sum_{k=1}^{K}n_k^{hu}+n_k^{hd}\le 4N \quad k\in K \tag{26}$$

$$n_{k+1}^{hp}=n_k^{hp}+n_k^{hu}-n_k^{hd} \quad \forall k\in K \tag{27}$$

$$n_k^{hp}P_{\min}^{hp}\le P_k^{hp}\le P_{\max}^{hp}n_k^{hp} \quad \forall k\in K \tag{28}$$

$$P_{\min}^{hg}\cdot t_k^{hp}\le P_k^{hg}\le P_{\max}^{hg}\cdot t_k^{hp}\cdot N \quad \forall k\in K \tag{29}$$

$$t_k^{hp}=1-n_k^{hp}\big/N \tag{30}$$

$$n_k^{hp},n_k^{hu},n_k^{hd}\in\{0,1,...,N\} \ \forall k\in K \tag{31}$$

$$t_k^{hp}\in\{0,1\} \quad \forall k\in K \tag{32}$$

where, $P_{thm}^{\min}$ and P_{thm}^{max} are the minimal and maximal power output of thermal unit, respectively; $\Delta P_{thm}^{\min}$ and $\Delta P_{thm}^{\max}$ are the minimal and maximal power step change of thermal unit, respectively; t_k^{thm} is the binary decision variable: "1" if thermal unit is on in period k; "0" otherwise{0,1}; V_k^{hu} and V_k^{hd} are the volume of upper and lower reservoir, respectively; $V_{\min}^{hu}$ and $V_{\max}^{hu}$ are the minimal and maximal limits of the upper reservoir, respectively; $V_{\min}^{hd}$ and $V_{\max}^{hd}$ are the minimal and maximal limits of the lower reservoir, respectively; H_p and H_g are the pumping and generating water flow of the pumped hydro plant, respectively; $\delta_{\min}^{hu}$ and $\delta_{\max}^{hu}$ are the allowable minimal and maximal volume change, respectively; N is the number of pumped hydro units; n_k^{hp} is the number of pumping units; n_k^{hu} and n_k^{hd} are the number of pumping units started up and shut down, respectively; $P_{\min}^{hp}$ and $P_{\max}^{hp}$ are the minimal and maximal pumping power of hydro unit, respectively; $P_{\min}^{hg}$ and $P_{\max}^{hg}$ are the minimal and maximal generating power of hydro unit, respectively; t_k^{hp} is the binary decision variable"0" if pumped units are pumping, "1" otherwise{0,1}; η_p and η_g are the efficiency of the pumping cycle of the pumped storage station, respectively.

Constraints (20)-(22) represent the volume limit of the upper and lower reservoir. The water balance constraints are shown in (23)-(26). Constraint (27) represents the volume change between the beginning and end of a single day. Every set of pumped hydro unit is limited to startup and shutdown at most twice every day, so the total times cannot exceed 4N, as shown in (28).The change in the number of pumping units is defined (29). Constraints (30)-(31) represent the pumping and generating power limit of the pumped unit, and also guarantee that the pumped hydro unit does not work simultaneously as a pump and a turbine by means of the binary variable t_k^{hp} . This variable is set to a null value by (32) when any of the units is working as a pump.

This is a multi-objective optimization problem. To solve this problem, the lexicographic method is chosen. This approach is suitable for the problem whose goals can be categories into different levels of preemptive priorities (Deb, 2001). By this way, the multi-objective optimization problem can be transferred into two sequent single-objective optimization problems. Here, the first objective is ranked first. Each problem contains quadratic constraints and semi-continuous variables, which can be solved by optimization software ILOG Cplex.

3.3 Case Study

A test system is created based upon the parameters of the wind-pumped hydro system by Ding et al. (2012). The pumped hydro plant is designed as 3% of the scale of the Bath County Pumped Hydro Storage Plant in in the USA. The parameters are shown in Table 3. Table 4 indicates the parameters of the thermal unit, which is based on the parameters given by Wang et al. (2013).

Table 3. Parameters of pumped hydro storage

$V_{\min}^{hu}$	$V_{\max}^{hu}$	$V_{\min}^{hd}$	$V_{\max}^{hd}$
481.5	1314	296.7	1129.2
$P_{\min}^{hp}$	$P_{\max}^{hp}$	$P_{\min}^{hg}$	$P_{\max}^{hg}$
10	13	6	15
H_g	H_p	η_p	η_g
329.2	335.3	0.907	0.927
$\delta_{\min}^{hu}$	$\delta_{\max}^{hu}$	π_{hu}	π_{hd}
-42	42	1000	1000

Table 4. Parameters of thermal unit

$P_{thm}^{\min}$	P_{thm}^{max}	$\Delta P_{thm}^{\min}$	$\Delta P_{thm}^{\max}$
12.5	50	15	-15
a	B	c	Start up Fuel
373.8	44.8	0.03	224

Electricity price within the period of 9:00-23:00 is 0.8 ¥/kWh, and the price within the period the period of 23:00-9:00 the next day is 0.4 ¥/kWh (¥ is China Currency).

Data of typical daily provincial load and data of the wind farm forecast are shown in Fig. 5 by curve.

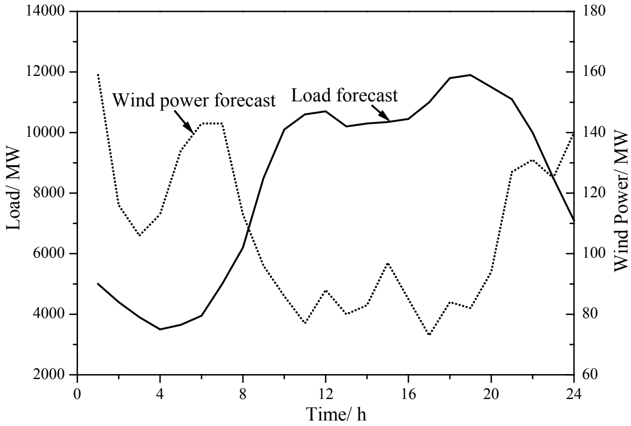

Fig. 5. Wind power forecast and load forecast

The optimization results for thermal unit and pumped-hydro storage are shown in Fig. 6-9. Fig. 6 indicates that the output of wind-thermal-pumped hydro system is correlated with the system load as we expected. The generating power of thermal unit and pumped hydro system are given in Fig. 7. The numbers of pumping unit starting up and shutting down for each period are shown in Fig. 8. The water volumes of upper and lower reservoirs are given in Fig. 9.

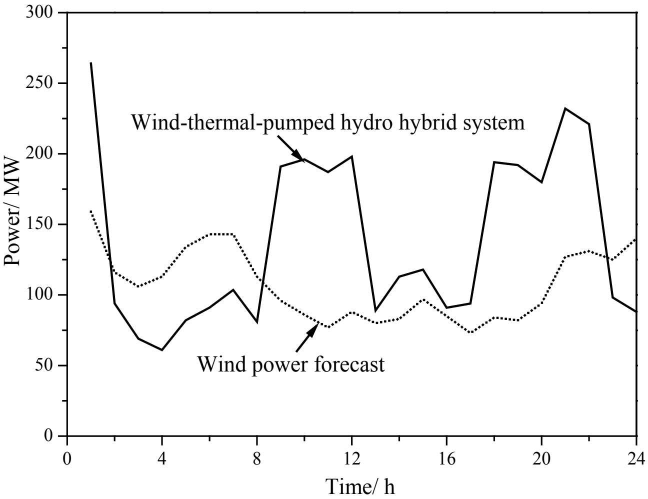

Fig. 6. Optimization results of wind-thermal-pumped system

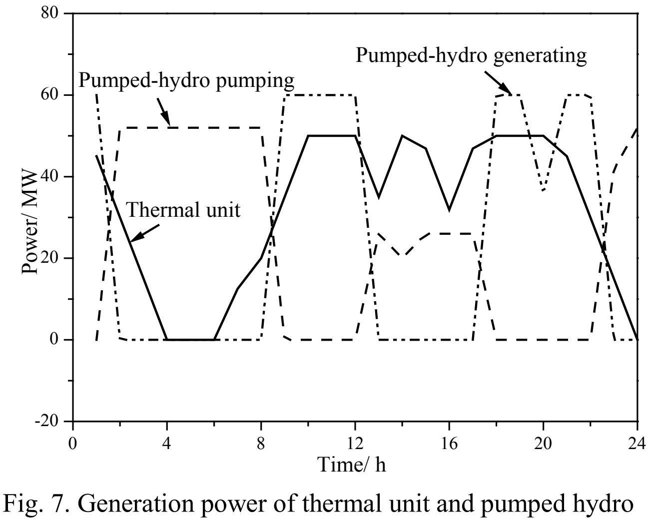

Fig. 7. Generation power of thermal unit and pumped hydro system

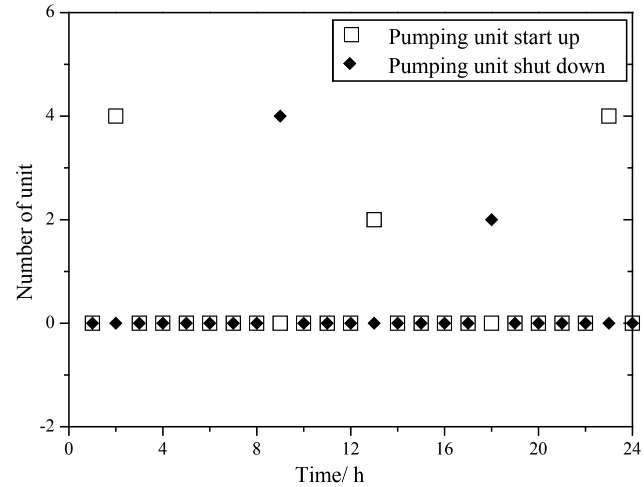

Fig. 8. Start up and shut down of pumped hydro system

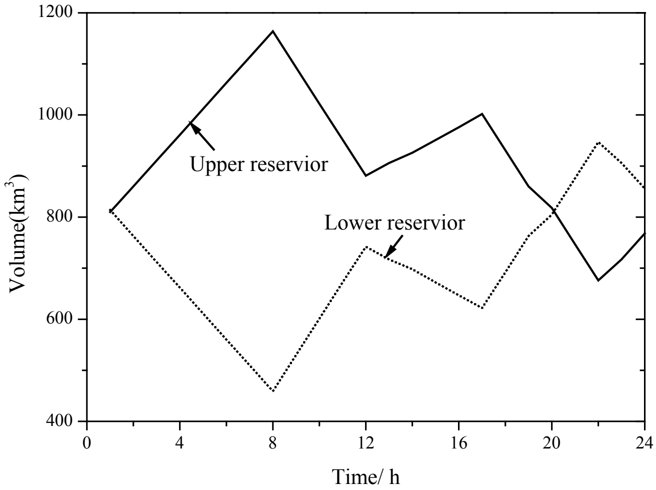

Fig. 9. Upper and lower reservoirs

4. CONCLUSIONS

The current paper discusses the choice of control objective in the field of coordinating wind energy and other sources. The key idea is that the control objective should match with the operation requirements of power systems. For each control objective, it is necessary to formulate corresponding model and explore the solving algorithm.

Based on the above principle, two examples are given. Firstly, the coordinated optimal control of wind-storage system is proposed and the coordination objective is to meet the ramp rate limit of grid code. Secondly, the coordinated optimal dispatch of wind-thermal-pumped hydro system is proposed and the coordination objective is to make the output of the combined system more correlated with the system load. The operation strategies can be promoted and generalized to other applications in different power systems.

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REFERENCES

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms.* 70. John Wiley & Sons, Chichester.

Ding, H., Hu, Z., & Song, Y. (2012). Stochastic optimization of the daily operation of wind farm and pumped-hydro-storage plant. *Renewable Energy*, **48**, 571-578.

Garcia-Gonzalez, J., de la Muela, R. R., Santos, L. M., & González, A. M. (2008). Stochastic joint optimization of wind generation and pumped-storage units in an electricity market. *IEEE Transactions on Power Systems*, **23(2)**, 460-468.

Greenblatt, J. B., Succar, S., Denkenberger, D. C., Williams, R. H., & Socolow, R. H. (2007). Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation. *Energy Policy*, **35(3)**, 1474-1492.

Kim, Y. H., Lee, J. S., & Kang, Y. C. (2012, April). Supervised shutdown algorithm for an offshore wind power plant to meet the required ramp rate of a grid code in a storm-driven situation. In *11th International Conference on Developments in Power Systems Protection.* DPSP 2012. (pp. 1-5). IET.

Miller, N., & Marken, P. E. (2010, July). Facts on grid friendly wind plants. In *Power and Energy Society General Meeting, 2010 IEEE* (pp. 1-7). IEEE.

Saejia, M., & Ngamroo, I. (2012). Alleviation of power fluctuation in interconnected power systems with wind farm by SMES with optimal coil size. *IEEE Transactions on Applied Superconductivity,* **22(3)**, 5701504-5701504.

Sioshansi, R. (2010). Welfare impacts of electricity storage and the implications of ownership structure. *Energy Journal*, **31(2)**, 173.

Teleke, S., Baran, M. E., Huang, A. Q., Bhattacharya, S., & Anderson, L. (2009). Control strategies for battery energy storage for wind farm dispatching. *IEEE Transactions on Energy Conversion,* **24(3)**, 725-732.

Vigueras-Rodrıguez, A., Sørensen, P., Cutululis, N. A., Viedma, A., Gómez-Lázaro, E., & Martin, S. (2009, March). Application of ramp limitation regulations for smoothing the power fluctuations from offshore wind farms. In *European Wind Energy Conference and Exhibition (EWEC09), Marseille (France).*

Wang Q, Watson J P, Guan Y. Two-Stage Robust Optimization for-Contingency-Constrained Unit Commitment, *IEEE Transactions on Power Systems*, **28(3)**, 2366-2375. 2013.