Study on Cross-Area System Operation Utilizing Pumped-Storage Hydro with Bulk Penetration of PVs

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Abstract. In Japan, PV as renewable energy source (RES) is expanding rapidly. However, if the PV penetration becomes too large, the regulation capability for maintaining the system frequency will be insufficient. Where such a problem arises, cross-area system operation that uses regulation capability of other systems through interconnection lines is being studied. This paper proposes the method of maintaining regulation capability by pumped-storage hydro in other electric power systems through changing the base tie line power flow.

Key words

Cross-area system operation, Base tie line power flow, Photovoltaics, Pumped-storage hydro, Load frequency control, Regulation capability

1. Introduction

Recently, interest has increased in photovoltaic (PV) as a clean energy source, and the Japanese government has promoted introduction of PV. In Japan, the penetration of PV at the end of 2016 reached 40.6 GW, which is expected to increase sharply to 71.62 GW which is a growth of about 1.8 times in 10 years⁽¹⁾. If the PV is interconnecting as it is, problems such as surplus power generation during peak PV output, insufficient output change speed of thermal unit may occur. In fact, on sunny days in spring when the demand is low, there are many occurrences in which the PV output occupies the majority of the demand. In Japan, there are many pumped-storage hydropower stations that work like a battery. Therefore the surplus PV output is reserved at pumped-storage hydro by lowering the upper pond water level in advance.

On the other hand, the Japanese electric power system is composed of a longitudinal transmission system unlike meshed power systems as in Europe due to geographical constraints. Each electric power system is basically interconnected with only one tie line route, and the supply and demand unbalance within its own system is adjusted by Tie Line Power Flow Frequency Bias Control (TBC). In 2015, the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) was established, and began cross-area supply and demand adjustment beyond

each electric power system. Cross-regional supply and demand regulation utilizes the regulation capability of other systems in case of shortage of self-system regulation capability due to bulk penetration of RES. A method of utilizing the margin capacity of the tie line to transmit constant power to another system has been studied (see Fig.1).

In this study, as a measure to cope with shortage of regulation capability at the time of bulk penetration of PV, a method to secure the regulation capability by changing the base tie line power flow (P_0) and utilizing the pumped-storage hydro in other systems will be studied.

2. Proposed Method

A. Outline

It is assumed that surplus power occurs in System A with a large PV interconnection when thermal power units have reached their minimum output limit during PV output peak period. At first surplus power is reserved by pumped-storage hydro in the system. However, when surplus power exceeds the installed capacity of pumped-storage hydro during PV output peak period, electric power which cannot be consumed (net surplus power) is transmitted to System B through increase of base tie line power flow (P_0). At this time, since thermal power units in System B may also reach their minimum output limit due to PV output increase in System B, the increase in P_0 is absorbed by the pumped-storage hydro through

Fig. 1. Base tie line power flow change image

pumping water up. With System A, it is possible to increase the output of the load frequency control (LFC) unit (thermal power unit) with the increase of P_0 , and the small regulation capability expands. Therefore, even when a large amount of PV is introduced, the power quality can be maintained without suppressing the PV output.

B. Pumped-Storage Hydro Response

Here, studied are the methods for suppressing transient frequency fluctuation caused by P_0 change and pumping up. Former study ⁽²⁾, assumed that all pumped-storage hydro are variable speed type. In the case of constant speed type, the pumping up quickly reaches the maximum. Therefore, on P_0 change, compared are two cases between a variable speed type which is possible to freely change the pumping speed and the time to reach the maximum input, and a constant speed type where the maximum input is reached in a short time.

First, the constant speed type will be explained. In this study, since TBC is assumed in each system, each system adjusts only the supply-demand unbalance ΔP in its own system. In the case of the constant speed type, since "power received due to P_0 change" and "consumed power by pumping up" is almost the same in System B (ΔP_B) does not occur. On the other hand, in System A, ΔP_A occurs because the output of the LFC unit cannot follow the sudden P_0 change. Therefore, since the sum of ΔP_A and ΔP_B increases, the frequency fluctuation ΔF increases in the constant speed type.

Next, the variable speed type will be explained. Taking into consideration that ΔP occurs only in System A with the constant speed type, the pumping up of System B is delayed and adjusted. By doing this, the sum of ΔP_B and already occurred ΔP_A approaches 0, and transient frequency fluctuation can be suppressed.

Since the constant speed type is the main stream, it is desirable to adopt a method presuming that the pumping up will reach the maximum input immediately. Therefore, in order to suppress the transient frequency fluctuation, a method of performing P_0 change with a small amount / multiple times is proposed. Transient frequency fluctuation can be suppressed by setting the P_0 change amount at one time to a small amount. Here, we are assuming that PV output changes slowly at sunny all day. Thereby, it is possible to maintain the supply-demand balance with a small amount / multiple times of P_0 change. On the contrary, for example, when the sky is cloudy and changes suddenly sunny at noon, the PV output suddenly increases. As the required P_0 change amount also increases (see Fig.2), the supply-demand balance might be difficult only

Fig. 2. PV and P_0 image from cloudy to sunny

by a method of making small P_0 change amount / multiple times.

C. P_0 Change Amount

The appropriate P_0 change amount is considered to be such a value that the output of the LFC unit reduced by PV net surplus power to maintain the supply-demand balance can be returned to the initial value each time P_0 is changed. In other words, P_0 is as same as the net surplus electricity amount. Since P_0 change interval is generally 15 minutes, one fourth of net surplus power per hour is appropriate for P_0 change amount per one time.

D. Proposed Method

Assuming the constant speed type pumped-storage hydro, P_0 change method to suppress transient frequency fluctuation is proposed.

Pumping up timing delay

Pumping up of System B starts at the same time with P_0 change. In this case, transient frequency fluctuations become very large because pumping up input reaches the max quickly while LFC units output change speed are relatively low. To suppress frequency fluctuation a method to delay pumping up timing and to adjust LFC unit output is considered. As shown in Fig.3, supply and demand unbalance ΔP occurs in each system with P_0 change, and an output adjustment signal is sent to each LFC unit ((A) in Fig.3). Apparent demand rapidly increases in System A due to P_0 change. Accordingly, LFC unit increases the output at the maximum output change speed and tries to maintain the supply and demand balance ((B) in Fig.3). The LFC unit, however, can't keep up with sudden change in P_0 and the unbalance ΔP_A occurs, as well as, ΔP_B in System B ((C) in Fig.3). At this time, If the number of commitment units in System A is large, units output can follow the signal quickly, and as a result the frequency gradually rises ((D) in Fig.3). Start timing of pumping-up in System B is decided somewhat before rising. For the constant speed type, it reaches the same amount of input power as P_0 change in several ten seconds. As the LFC unit in System B cannot follow up and ΔP_B occurs, the frequency rapidly decreases until reaching the maximum pumping up ((E) in Fig.3). The key point of this proposed method is to raise the frequency by utilizing the difference of the maximum output change speed of LFC units in each system, to start pumping-up at a timing when it rises to a certain extent, and to keep the sudden frequency drop

Fig. 3. Image of proposed method

within the admissible range (e.g. $\pm 0.1\text{Hz}$).

The pumping start timing $y[s]$ that most suppresses the transient frequency fluctuation can be calculated from the relationship of the equation (1) when the P_0 change amount is $x[\text{MW}]$.

$$y + \frac{(\text{Speed}_A + \text{Surplus} - \text{Speed}_B) \times y}{\text{Pumped}} = \text{Signal} + \frac{x}{\text{Speed}_A + \text{Surplus}} \quad (1)$$

where,

- x [MW]: P_0 change amount
- y [s]: Pumping start timing
- Speed_A [MW/s]: Total maximum output change speed of System A
- Speed_B [MW/s]: Total maximum output change speed of System B
- Surplus [MW/s]: Net surplus power change speed
- Pumped [MW/s]: Pumped-storage hydro pumping up speed
- Signal [s]: LFC signal delay time

If ΔP_A is a positive value when the frequency decreases the most, frequency drop can be suppressed. Therefore, the pumping start timing that the Area Control Error (ACE) of each system returns to 0 at the same time can suppress the frequency deviation most. The left side of the equation (1) represents the time until the frequency deviation returns to 0 after P_0 change. The right side of the equation (1) represents the time until ΔP_A returns to 0 after P_0 change.

By using equation (2) in addition to equation (1), it is possible to calculate the maximum P_0 amount that falls within the frequency $\pm 0.1\text{Hz}$.

$$x = (\text{Speed}_A + \text{Surplus} - \text{Speed}_B) \times y + \text{Capacity} \times K \times 100 \times 0.1 \quad (2)$$

where,

- Capacity [MW]: Total system capacity $\hat{=}$ Total demand
- K [%MW/Hz]: System constant

Equation (2) represents supply-demand unbalance ΔP from the start of pumping up to reaching the maximum input (see Fig.4). When the P_0 change amount is x , the pumping up amount is also x . Beginning pumping up of x ,

Fig. 4. Image of eq.(2)

ΔP becomes x because the LFC unit cannot respond to sudden pumping up. The first term on the right side represents how much ΔP changed from the start of P_0 change to the start of pumping up. Since it is only necessary to calculate $\Delta P_A + \Delta P_B$, it is obtained by the difference of the output change speed of each system. The second term represents ΔP at which the frequency deviation maintains within $\pm 0.1\text{Hz}$. This can be calculated from the system capacity and the system constant.

3. Simulation Conditions

In this study, short-term components of PV output are not taken into consideration in order to compare and investigate methods for suppressing transient frequency fluctuation caused by P_0 change and pumping up. In addition, long-term components of demand fluctuation and PV output are not taken into consideration as they have been adjusted by EDC schedule. The simulation time is 1 hour from 12 o'clock which is the PV output peak time (see Table 1). At this time, P_0 is changed in the same way as maintaining the supply-demand balance. The net surplus power which cannot be adjusted by EDC is modeled as a ramp function. The simulation software uses MATLAB and Simulink.

A. Target System

The target system is composed of System A (33134MW) with a large PV introduction amount (31840MW) and System B (14181MW) with a small PV introduction amount (8290MW), interconnected by one tie line.

B. Generation Schedule

The proposed method is studied under the same conditions as in reference⁽²⁾. Data such as demand, generation schedule, PV output and the operation method of the LFC unit are used. The installed capacity of the pumped-storage hydro is 9996MW (System A) and 3360MW (System B).

Table 1. Surplus power and net surplus power of peak-time

Time[h]	Surplus power [MW]	Power exceeding installed capacity of Pumped-storage[MW]	Difference from previous time [MW]
10	9309	0	0
11	11848	1852	1852
12	13352	3356	1504
13	12498	2502	-855
14	10417	421	-2081

Table 2. Maximum output change speed

	System A	System B	PV output
Oil and LNG-fired [MW/s]	4.611	1.454	0.932
CC [MW/s]	0.268	3.272	
Sum [MW/s]	4.879	4.726	

Table 3. Maximum frequency deviation

P_0 amount [MW]	How to change P_0	Max frequency deviation [Hz]
630	No pumping delay	-0.127
630	Proposed method	-0.100
840	No pumping delay	-0.171
840	Proposed method	-0.138

4. Simulation

A. Verification of Pumped-Storage Hydro

Two cases with both types of the pumped-storage hydro are compared by numerical simulation. Here, while the constant speed type is assumed to reach the maximum pumping up in 1 minute, the variable speed type in 30 minutes. In order to perform this verification, a ramp function of 1500MW of the net surplus power is input to System A, and the same amount of 1500MW P_0 change is

(a) PV output, P_0 and Pumping up

(b) Oil and LNG-fired output (System B)

(c) Unbalance in supply and demand within each system

(d) Frequency deviation

Fig. 5. Comparative verification of pumping up type

input, both made 15 minutes after the start of the simulation.

B. Simulation Date

The maximum P_0 change amount that can be kept within $\pm 0.1\text{Hz}$ is 630MW, after 125s from the values calculated based on data in Table 2 and equation (1), (2). However, for example, if it is cloudy before noon and becomes sunny at noon where the PV output

(a) PV output, P_0 and Pumping up

(b) Oil and LNG-fired output (System B)

(c) Unbalance in supply and demand within each system

(d) Frequency deviation

Fig. 6. P_0 changing amount of 630MW

suddenly increases, it is necessary to change P_0 at 840MW ($3356\text{MW} \div 4$) every 15 minutes. At this time, the pumping up starts 160s after the simulation start.

C. Evaluation Method

The transient frequency fluctuation with P_0 change based on the proposed method is evaluated. Regarding frequency, management target of Japanese power systems is generally $\pm 0.2\text{Hz}$ of the power system frequency. In this study within 0.1Hz is applied in order to verify the method.

D. Simulation Results

Table 3 summarizes the transient maximum frequency deviation when the maximum P_0 change amount is 630MW with / without the proposed method. Fig. 5 shows the comparison and verification results with both types of pumped-storage hydro. By pumping up slowly, the thermal unit is responding with the maximum output change speed ((a), (b) in Fig.5). However, since P_0 change amount is large, ΔP_B is occurred ((c) in Fig.5). By pumping up of the variable speed type, the sum of ΔP_A and ΔP_B approaches 0, and transient frequency deviation can be suppressed ((d) in Fig.5).

(a) PV output, P_0 and Pumping up

(b) Oil and LNG-fired output (System A)

(c) Frequency deviation

Fig. 7. Results of the proposed method

Fig.6 shows that the pumping up timing is delayed 125s by the proposed method ((a) in Fig.6). If pumping delay is made, the LFC unit reduces the output at the maximum output change speed and respond with it, and the unbalance appears as large as ΔP_B ((b), (c) in Fig.6). Since the output adjustment speed of System A is higher, the frequency gradually rises until the pumping up is started ((d) in Fig.6). Although the frequency greatly decreases with pumping start, it is within -0.1Hz with almost no error.

Fig.7 shows the result of applying the proposed method at an appropriate P_0 change amount of 840MW with pumping delay. The LFC unit in System A can maintain almost the same regulation capability as the initial value ((b) in Fig.7). Also, although the pumping up amount to be changed at one time is large, by using the proposed method, the transient frequency deviation can be effectively suppressed as compared with the case where pumping delay is not performed ((c) in Fig.7).

5. Consideration

By the simulation so far, it was confirmed that the power quality can be maintained by using P_0 change and pumped-storage hydro during PV output peak. Only in the daytime operation, however, the capacity ratio of the upper pond in System A exceeds 90%. It is possible to lower the upper pond water level by generation from early evening when the PV output decreases. Considering the storage efficiency of pumped-storage hydro, 70%, Fig.8 shows that it is possible to lower the upper pond water level from almost the full level in the day time by generation during night time, and the consecutive operation is possible on the next day. In addition, due to bulk penetration of PV, there is a concern about so-called "duck curve" due to lack of LFC unit in the early evening. Pumped-hydro generation can relieve the output

Fig. 8. Generation scheduling of System A (Nuclear Power 33%)

Fig. 9. Changing of upper pond water level of System A

sudden increase of the LFC unit and stable operation is possible. Fig.9 shows upper pond water level of System A. It is shown that it is possible to almost empty the upper pond water level during one day operation. If it is expected that the PV output will increase due to the sunny weather forecast, it is necessary to make the pond near empty at the dawn.

In the future power system, it is assumed that nuclear power plant will run as much as before. In other words, it is considered that spring holiday with low demand is a severe case where excess power supply of daytime occurs due to bulk penetration of PV. However, when the base power supply ratio including nuclear power plant is high, Fig.8 shows that the duck curve problem as described above does not occur. On the other hand, Fig.10 shows daily generation schedule without nuclear power plant. This shows that little surplus power in the daytime occurs and PV output can be effectively utilized. However, because the amount of pumping up power is small and pumped-hydro generation cannot be effectively used early evening, thermal unit output increases rapidly. Fig.11 shows the commitment ratio of oil and LNG-fire unit corresponding to the ratio of nuclear power plant. It means that when the nuclear power plant ratio becomes low, oil and LNG-fire will have to start and stop frequently. In other words, it is impossible to satisfy the unit minimum operation/stop time constraints. Base power including nuclear power plant is necessary not only from the economy viewpoint but also in terms of mitigating the duck curve problem. In the case of bulk penetration of PV, the ratio of base power plant should be planned, taking excess supply problem during daytime into consideration.

Fig. 10. Generation scheduling of System A (No Nuclear Power Plant)

Fig. 11. Commitment ratio of Oil and LNG-fire corresponding to nuclear power ration

6. Conclusion

We have proposed a method to secure the regulation capability by pumped-storage hydro of other systems through changing P_0 . Pumped-storage hydro is assumed not only for variable speed type, but also constant speed type which is generally introduced. As a result of comparative study, the variable speed type is more desirable. In certain cases, however, it has been confirmed that a method of delaying pumping up timing is suitable as well with the constant speed type. By the proposed method, it is possible to maintain power quality without suppressing PV output as much as possible.

In the future, novel method for generation scheduling in consideration with sudden weather change will be necessary. Risk assessment against weather forecast will be required as well.

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