

A fuzzy inference based method for evaluating coordinated generation-grid-load-storage control ability in receiving-end power system

Lu Yang¹, Yuanyang Chen², Yijia Cao¹, Changfeng Liao^{1*}, Yi Tan¹, Yong Li¹, and Siyuan Guo³

¹ College of Electrical and Information Engineering, Hunan University, Changsha, Hunan 410082, China

² State Grid Hunan Electric Power Company Limited, Changsha, Hunan 410004, China

³ Electric Power Research Institute, State Grid Hunan Electric Power Company Limited, Changsha, Hunan 410007, China

Abstract. With the rapid development of the flexible loads and energy storage, it is of great scientific and engineering value to improve safety and economy of the receiving-end power system with HVDC feed-in power by the coordinated generation-grid-load-storage control. In this paper, a fuzzy inference based method is proposed to assess the coordinated control ability of generation-grid-load-storage control for the receiving-end power system with HVDC feed-in power. First of all, the evaluation indexes are constructed with consideration of the coordination and interaction of power generation, power grid, power load and energy storage. Both subjective weight and objective weight are considered to calculate the comprehensive weight for each evaluation index. Furthermore, the Kmeans clustering based method is proposed to the grading in each evaluation index. Finally, the coordination control ability of the modified IEEE 57-bus system in different states is evaluated by the proposed method.

1 Introduction

The line commutated converter based high-voltage direct current transmission system (LCC-HVDC) is a solution to the efficient, safe and long-distance transmission of large scale energy [1]. The renewable energy fed into the receiving-end system via HVDC technology can greatly reduce the power supply pressure, but it also brings the adverse effects to the safe and stable operation of the receiving-end power system [2]. For example, the DC blocking can cause a large-scale power shortage in the receiving-end power system and traditional stability control methods such as the load shedding are difficult to work effectively in this situation [3]. The interaction and coordinated operation of power generation, power grid, power load and energy storage (denoted as generation-grid-load-storage in this paper) is very conducive to the dynamic supply-demand balance and the economic and safe power system operation [4]. Thus, this helps to improve the stability and security level of the receiving-end power system with HVDC feed-in power.

Research work has been done in the field of the generation-grid-load-storage optimization and control. Ref. [5] proposed an integrated generation-grid-load-storage operation method to realize the efficient operation of park microgrid by considering market transaction, auxiliary services and so on. With consideration of the operating costs, initial investment costs, pollutant emission costs, Ref. [6] proposed a cultural genetic algorithm based generation-grid-load-

storage scheduling method for hybrid AC/DC microgrid. Ref. [7] proposed a genetic algorithm based multi-period coordinated generation-grid-load-storage dispatch method for active distribution networks. Ref. [5-7] mainly focused on the coordinated generation-grid-load-storage control and optimization in small-scale power systems to reduce the operating costs. In contrast, Ref. [8] proposes a multi-objective generation-grid-load-storage dispatch method to reduce the costs and pollutant emissions by coordinating various controllable resources in bulk power systems.

With the rapid development of the fine load shedding, battery storage, the coordinated generation-grid-load-storage optimization and control are increasingly being emphasized by the academic community and the power industry. Consequently, it is necessary to research on the effective and reasonable assessment of the coordinated control ability of power generation, power grid, power load and energy storage. Thus, this paper presents the evaluation indexes by comprehensive consideration of the generation-grid-load-storage characteristics in the receiving-end power system with HVDC feed-in power. Also, this paper proposes the fuzzy inference based method for assessing the coordinated generation-grid-load-storage control ability.

2 Indexes for evaluation

This section proposes the evaluation indexes for the coordinated generation-grid-load-storage control

*Corresponding author's e-mail: liao cf@hnu.edu.cn

(GGLSC) ability in the receiving-end power system with HVDC feed-in power.

2.1 Fast frequency control

Thermal generating units and hydropower units are traditional frequency-control units in power systems. It is well known that thermal generating units have limited ramping rate and slow response speed and the water supply of hydropower generating units is unstable. The battery storage has fast response speed and flexible adjustment ability which can realize fast frequency control [9].

Considering the rapid response characteristics of the battery storage, the fast frequency control ability (T_{FFMA}) is defined as follows.

$$T_{FFMA} = \frac{\alpha'_{ch} P'_{ch}}{P_L} + \frac{\beta'_{dis} P'_{dis}}{P_L} \quad (1)$$

where P'_{ch} is the fast charging power of the battery storage and P'_{dis} is the fast discharging power of the battery storage. P_L is active power demand of the receiving-end power system. α'_{ch} is the weight coefficient of the fast charging of the battery storage, and β'_{dis} is the weight coefficient of the fast discharging power of the battery storage.

2.2 Total frequency control ability

By considering the frequency control ability of thermal power units, hydropower units and battery storage [10], and the total frequency control ability (T_{TFMA}) of the receiving-end power system is defined as follows:

$$T_{TFMA} = T_{TFMA}^h + T_{TFMA}^s + T_{FFMA} \quad (2)$$

$$T_{TFMA}^h = \frac{\alpha_u^h P_u^h + \beta_d^h P_d^h}{P_L} \quad (3)$$

$$T_{TFMA}^s = \frac{\alpha_u^s P_u^s + \beta_d^s P_d^s}{P_L} \quad (4)$$

where T_{TFMA}^h is the frequency control ability of the thermal units. P_u^h is the ramping-up power of the thermal units. P_d^h is the ramping-down power of the thermal units. The α_u^h and β_d^h are the weight coefficients of the P_u^h and P_d^h , respectively. T_{TFMA}^s is the frequency control ability of hydropower units, P_u^s is the ramping-up power of hydropower units, P_d^s is the ramping-down power of hydropower units. The α_u^s and β_d^s are the weight coefficients of P_u^s and P_d^s , respectively.

2.3 Peak load adjustment

Considering the peak-load adjustment ability of thermal power units, hydropower units and energy storage systems [11], the peak-load adjustment ability (ψ_{PLRA}) is defined as follows:

$$\psi_{PLRA} = \frac{R_b^h + R_b^s}{P_L} + \frac{2C_b^x}{T_p P_L} \quad (5)$$

where R_b^h is the reserve capacity of the thermal units. R_b^s is the reserve capacity of the hydropower units. C_b^x is the rated energy of the battery storage, and T_p is the total time for the battery storage to participate in peak-load adjustment.

2.4 HVDC feed-in Power

This paper assumes that external renewable energy such as remote wind power are fed into the receiving-end power system via HVDC. The characteristics of the wind power that transmitted by HVDC can reflect the stable level of the receiving-end system and the coordinated GGLSC ability to a certain extent [12]. Thus, the following index related to wind power that transmitted by HVDC is proposed to evaluate the coordinated GGLSC ability of the receiving-end power system:

$$\gamma_{WG} = \alpha_{unc} \frac{P_L}{P_{LCC,Wind}} + \beta_{adj} \lambda_{adj} P_{LCC,Wind} \quad (6)$$

where the first part on the right side of (6) reflects the uncertainty of wind power, and the latter part reflects the adjustment ability of wind power. $P_{LCC,Wind}$ is the wind power transmitted via HVDC. α_{unc} and β_{adj} are the coefficient weights to determine the importance of wind power uncertainty and wind power controllability, respectively. λ_{adj} is a coefficient reflecting the relationship between the controllability and wind power.

2.5 Reactive power support

The reactive power support from the receiving-end power system can reduce the probability of unipolar blocking of HVDC converters [13]. In this paper, the reactive power support ability is defined as follows:

$$\varepsilon_z = \frac{Q^t + Q^h + Q^s + Q^x}{Q_L + Q^{HVDC}} \quad (7)$$

where Q^t is the reactive power output of the synchronous condenser. Q^h and Q^s represent the reactive power outputs of thermal and hydroelectric power plants, respectively. Q^x is the reactive power output of the battery storage. Q^{HVDC} is the reactive power absorbed by the HVDC system. Since the quantity of Q^{HVDC} is equal about 40% of the quantity of the active power of the HVDC system [14], Q^{HVDC} is

assumed to be 40% of the active power of the HVDC system in quantity in this paper. Also, it is assumed that 50% of the active power transmitted by HVDC comes from external wind power and the rest is from external thermal power plants. Q_L represents the reactive load within the receiving-end power system.

2.6 Voltage stability

The stability level reflects how effective the coordinated GGLSC will be to a certain extent [15]. In order to consider the voltage stability margin of the AC bus that the HVDC converter is connected and the voltage stability margin of other buses in the receiving-end power system, the following voltage stability index are proposed:

$$\delta^c = \alpha_V \frac{V_{HV} - V_{HV,cr}}{V_{HV}} + \beta_V \max_i \left\{ \frac{V_i - V_{i,cr}}{V_i} \right\} \quad (8)$$

where V_{HV} is the voltage of the AC bus that the HVDC converter is connected. $V_{HV,cr}$ is the well-known critical voltage of the PV curve of the AC bus that the HVDC converter is connected. V_i and $V_{i,cr}$ represent the voltage and the well-known critical voltage of the PV curve of bus i (except the AC bus that the HVDC converter is connected) in the receiving-end power system. α_V and β_V are the weight coefficients for considering different parts of the receiving-end power system.

2.7 Rough load shedding and fine load shedding

Rough load shedding (RLS) and fine load shedding (FLS) reflect the stability control ability of flexible load [16]. The shedding precisions of the RLS and the FLS are different, thus this paper proposes the weighting of the RLS and the FLS to evaluate the coordinated GGLSC ability:

$$v_k = \frac{\alpha_m L_m + \beta_j L_j}{P_L} \quad (9)$$

where L_m is the load that the RLS system can shed, and L_j represents the load that the FLS system can shed. The

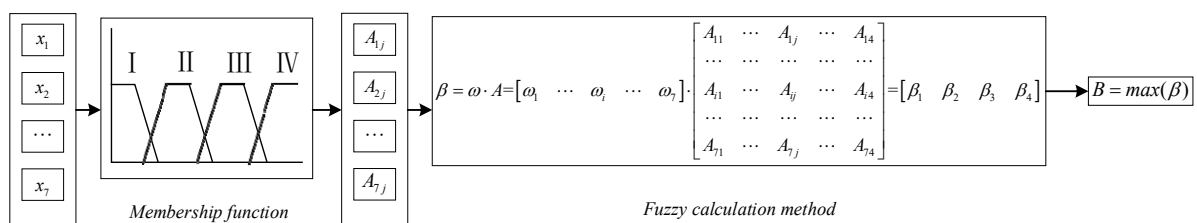


Figure 1. Fuzzy rules in this paper.

3.2 Calculation of the weight

Due to the different importance of different evaluation indexes, weight ω_i is used to distinguish the importance of different evaluation indexes. This paper uses the

α_m and β_j are the weights of RLS and FLS, respectively.

3 Comprehensive evaluation method based on fuzzy inference

3.1 Fuzzy inference

Fuzzy inference based evaluation can make a comprehensive assessment by considering many factors, thus it is widely used in power system evaluation, control and other fields [17]. Fuzzy logic generally contains four parts, i.e., fuzzification, fuzzy rules, fuzzy inference, and defuzzification [18]. In this paper, the coordinated GGLSC ability evaluation is based on the widely used Mamdani fuzzy reasoning [19]. When the input is A , Mamdani-type fuzzy inference calculates the output B as follows:

$$B = A \circ (C \rightarrow D) \quad (10)$$

where $C \rightarrow D$ and \circ represent fuzzy rules and fuzzy operation, respectively. A is the membership matrix for the fuzzified evaluation indexes and B is the evaluated grade of the result. The fuzzy membership function of the Mamdani operation is

$$\mu_B(y) = \bigvee_{x \in X} \mu_A(x) \wedge [\mu_C(x) \wedge \mu_D(y)] \quad (11)$$

The fuzzy rules used in this paper can be expressed in Figure 1, where $x_1, x_2, x_3, x_4, x_5, x_6$ and x_7 correspond to the evaluation indexes $T_{FFMA}, T_{TFMA}, \psi_{PLRA}, \gamma_{WG}, \varepsilon_z, \delta^c$ and v_k , respectively. The level of coordinated GGLSC ability in this paper is divided into four levels, i.e., Level I, Level II, Level III and Level IV, which correspond to “poor coordinated GGLSC ability”, “qualified coordinated GGLSC ability”, “good coordinated GGLSC ability” and “excellent coordinated GGLSC ability”, respectively. The row vectors $A_{1j}, A_{2j}, A_{3j}, A_{4j}, A_{5j}, A_{6j}, A_{7j}$ ($j=1, 2, 3, 4$) are the membership vector of fuzzified evaluation indexes corresponding to the j th coordinated GGLSC ability level. β is membership vector of the weighted evaluation indexes. B is the level of the coordinated GGLSC ability.

combination of the objective weight and the subjective weight to construct the comprehensive weight of the evaluation indexes.

The objective weights are calculated using the anti-entropy method [20]. Assume that the evaluation matrix

of the proposed indexes is $M = (x_{ij})_{n \times m}$, the anti-entropy value of each index can be calculated as follows:

$$h_i = -\sum_{j=1}^m r_{ij} \times \ln(1 - r_{ij}) \quad (12)$$

where $r_{ij} = x_{ij} / \sum_{j=1}^m x_{ij}$. The objective weight of index i can be obtained by normalizing the anti-entropy value.

$$\omega_{oi} = h_i / \sum_{i=1}^n h_i \quad (13)$$

The subjective weight of the experts is determined by the analytic hierarchy process method (AHP) [21]. Let the comparative matrix based on the three-demarcation [21] method be N . The subjective weight ω_{si} of index i is obtained as follows:

$$\omega_{si} = \xi_i / \sum_{i=1}^n \xi_i \quad (14)$$

where the ξ_i is obtained based on the following method: firstly, obtain the maximum eigenvalue λ_{max} of the comparison matrix N and the corresponding eigenvector vector ξ (whose i -th element is ξ_i). Then a consistency check is performed. If the consistency check is passed, the subjective weight ω_{si} is accepted; otherwise, reconstruct the comparison matrix N and repeat the previous process until the consistency test is passed.

After calculating the objective and subjective weights, the weight of the evaluation index is calculated as follows [22]:

$$\varpi_i = \omega_{oi} + \eta \omega_{si}, \quad i = 1, 2, \dots, n \quad (15)$$

where η is the coefficient for weighting the corresponding expert experience. The weight of each evaluation index is furthermore normalized to get the comprehensive weight of the evaluation index:

$$\omega_i = \varpi_i / \sum_{i=1}^n \varpi_i \quad (16)$$

3.3 The detailed process of the evaluation

Based on the proposed indexes and method, the coordinated GGLSC ability is evaluated as follows:

- 1) Calculate the objective weight ω_{oi} and subjective weight ω_{si} , and then calculate the comprehensive weight vector $\omega = (\omega_1 \ \dots \ \omega_i \ \dots \ \omega_7)$ for the seven evaluation indexes;
- 2) Based on Latin hypercube sampling [23], several wind speed scenarios and load scenarios are generated according to their probability distributions. Then, the wind power is calculated based on the relationship between the wind power and wind speed (see [24]). In this paper, the uncertainties of load and wind speed are described by the normal distribution [25] and the two-parameter Weibull distribution [26], respectively;
- 3) Calculate the evaluation index for each wind power and load pair. Then the Kmeans clustering algorithm is used to obtain four cluster centers for each index, which are used as a reference for dividing the four evaluation levels;
- 4) Establish the membership function for each evaluation index;
- 5) The valuation index $x_1, x_2, x_3, x_4, x_5, x_6$ and x_7 are calculated based on the predicted wind power and load. After that, calculate the element A_{ij} in the membership matrix of the evaluation index ($i=1,2,\dots,7, j=1,2,3,4$);
- 6) Calculate $\beta = \omega \cdot A$, and then evaluate the coordinated GGLSC ability by $B = \max(\beta)$. The B is the result of the defuzzification which represents the level of the coordinated GGLSC ability.

4 Simulation analysis

4.1 Test system

In this section, the IEEE 57 bus system [27] is modified for testing the proposed evaluation method. The modifications include the addition of wind power, battery storage and so on. The detailed modifications are shown in Table 1. Note that the wind power is injected into the modified IEEE 57 bus system via HVDC. That means wind power is part of the HVDC feed-in power.

Table 1. Detailed modifications

	HVDC feed-in power	Wind power	Synchronous Condenser	Battery storage	Hydropower	Flexible loads
AC Bus	38	\	38	36	11	29
Capacity	200MW	100MW	40MVar	120MW	80MW	100MW

4.2 Evaluation results

In this section, the coefficient η is assumed to be 0.618. Also, it is assumed that the evaluation matrix M and the comparison matrix N are as follows:

$$M = \begin{bmatrix} 0.08 & 0.04 & 0.05 & 0.16 & 0.12 & 0.22 & 0.32 & 0.06 & 0.24 & 0.20 \\ 0.19 & 0.29 & 0.10 & 0.08 & 0.18 & 0.16 & 0.10 & 0.13 & 0.01 & 0.18 \\ 0.18 & 0.05 & 0.13 & 0.18 & 0.08 & 0.08 & 0.23 & 0.03 & 0.03 & 0.24 \\ 0.14 & 0.01 & 0.27 & 0.20 & 0.09 & 0.13 & 0.01 & 0.19 & 0.12 & 0.13 \\ 0.19 & 0.16 & 0.04 & 0.05 & 0.19 & 0.02 & 0.16 & 0.15 & 0.20 & 0.08 \\ 0.18 & 0.26 & 0.23 & 0.24 & 0.08 & 0.20 & 0.12 & 0.22 & 0.25 & 0.03 \\ 0.04 & 0.19 & 0.18 & 0.09 & 0.26 & 0.19 & 0.06 & 0.22 & 0.15 & 0.14 \end{bmatrix} \quad N = \begin{bmatrix} 1 & 2 & 0 & 2 & 0 & 2 & 2 \\ 0 & 1 & 0 & 0 & 1 & 2 & 0 \\ 2 & 2 & 1 & 2 & 2 & 1 & 1 \\ 0 & 2 & 0 & 1 & 0 & 2 & 1 \\ 2 & 1 & 0 & 2 & 1 & 2 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 2 & 1 & 1 & 2 & 2 & 1 \end{bmatrix}$$

where the “0” in N means that a column element is more important than a row element, the “1” in N means that a column element is as important as a row element, and the “2” in N means that a row element is more important than a column element. For example, If the element in the first row and second column is 2, the element in the second row and first column must be 0. That is, the second index (x_2) is more important than the first one (x_1). If the element in the seventh row and third column is 1, then the third index (x_3) is as important as the seventh index (x_7). For the objective weight, the anti-entropy of each index is determined by the evaluation matrix M

according to the (12). Then the objective weight ω_{oi} is further calculated by the anti-entropy value according to the (13). For subjective weight, the consistency test of the comparison matrix N is conducted. After the consistency test is passed, the subjective weight of each indexes is determined according to (14). The results of the objective weight and subjective weight can be found in Table 2 in which the numbers 1 to 7 correspond to the evaluation indexes $x_1, x_2, x_3, x_4, x_5, x_6$ and x_7 , respectively.

After that, The comprehensive weights are calculated according to the (15)-(16), whose results are shown in Table 2.

Table 2. Weights of evaluation indexes.

Evaluated indicators	1	2	3	4	5	6	7
Objective weight	0.1527	0.1398	0.1550	0.1509	0.1417	0.1283	0.1316
Subjective weight	0.1759	0.0586	0.2647	0.0930	0.1547	0.0575	0.1955
Comprehensive weight	0.1616	0.1088	0.1969	0.1288	0.1466	0.1013	0.1560

After obtaining the comprehensive weight of each evaluation index, the values of the evaluation indexes are calculated for different scenarios of wind power and load which are generated by Latin hypercube sampling [23].

Then the Kmeans clustering analysis is carried out to obtain the clustering centers for different evaluation indexes, whose results are shown in Table 3. The membership function is established based on the Kmeans clustering results of each evaluation index.

Table 3. Kmeans clustering results of evaluation indexes

Evaluated indicators	1	2	3	4	5	6	7
I (Class 1)	0.0372	0.2228	0.2511	43.00	0.3734	0.0210	0.0569
II (Class 2)	0.0404	0.2535	0.2732	52.10	0.4476	0.0236	0.0675
III(Class 3)	0.0490	0.2792	0.3134	58.50	0.4772	0.0271	0.0789
IV(Class 4)	0.0538	0.2991	0.3390	62.40	0.5160	0.0352	0.0902

Three forecasted values of the load and six forecasted values of the wind power are analysed. As shown in Table 4, the coordination control abilities in most cases are in the levels of III and IV. With the increasing wind power and system load, the coordination control ability exhibits a decreasing trend. For example, the coordinated GGLSC abilities are in the levels of II and I when the

predicted load is 1632.99 MW. When the forecasted load is changed to be 995.3598 MW, the coordinated GGLSC control abilities are in the levels of III and IV.

Table 4. Evaluation results under different scenarios.

Forecasted wind power	#1 (0 MW)	#2 (22.9951 MW)	#3 (52.6294 MW)	#4 (76.7363 MW)	#5 (91.6752 MW)	#6 (100 MW)
Forecasted load #1 (1632.99MW)	II	II	II	II	II	I
Forecasted load #2 (1313.7 MW)	III	III	III	III	III	III
Forecasted load #3 (995.3598 MW)	IV	IV	IV	IV	IV	III

5 Conclusion

In this paper, the fuzzy inference method is used to give a comprehensive evaluation for the coordinated generation-grid-load-storage control ability in the receiving-end power system with HVDC feed-in power. The evaluation indexes are constructed from different aspects such as frequency control and voltage stability level. The modified IEEE 57-bus system is used to test the proposed comprehensive method for evaluating the coordination control ability. This paper can provide a reasonable reference for the development of the coordinated generation-grid-load-storage control strategy.

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