Study on Low Frequency Oscillation of Wind-solar Hybrid Generation System

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Abstract. Wind-solar hybrid generation system can significantly improve the utilization efficiency of intermittent renewable energy as it can make full use of the complementarity of wind-solar. Meanwhile, it will affect the low frequency characteristics of power system. Effect of different wind-solar accommodation conditions on low frequency oscillation characteristics of power system are analyzed based on IEEE 2-area 4-unit system. Eigenvalue analysis and dynamic time-domain simulation are adopted to figure out the influence, including different factors such as separate integration, grid-connected integration points and hybrid capacity ratios of wind-solar.

1. Introduction

The integrated energy system (IES) with multiple energy sources has become an important direction of energy structure adjustment in China in recent years, because it can coordinate optimization of energy through production, transmission, distribution, conversion, storage and consumption of various forms of energy [1]. The utilization efficiency of intermittent renewable energy such as wind-solar can be greatly improved by utilizing wind-solar to form a wind-solar hybrid generation system. However, large-scale wind-solar power integrated into power system will make the low frequency oscillation characteristics more complex.

In references [2-4], the impacts of the type, transmission distance, penetration level and location of wind farm on the oscillation mode of power system are analysed. Besides, these factors all have different degrees of effect on the system. The research results of reference [5] indicate that the damping ratios of critical modes in power system are improved with the increase of photovoltaic penetration level. References [6-7] show that the stability of photovoltaic power generation system will be affected by the factors of fault location, the permeability of photovoltaic array and the type of disturbance. The simulation results of reference [8] show that the transient voltage stability of system is better when the new energy penetration is less than 40%. It’s revealed in references [9] that the damping of the system is improved when the photovoltaic penetration increases while the wind penetration is only up to 50%. Reference [10] suggests that wind-solar hybrid generation system improves the large power fluctuation caused by wind farm or photovoltaic array grid-connected alone. Reference [11] shows that the damping is better when the synchronous machine is replaced by equivalent capacity of photovoltaic array than wind farm alone, while the system has the best damping when wind farm and photovoltaic array are integrated into the system at the same time.

It's not hard to see that most researches focus on the effect of independent wind-solar power on the static, transient and voltage stability of the system under different conditions. However, there is few...
systematic analysis of the influence of wind-solar hybrid generation system on low frequency oscillation. As we all known, the change of grid-connected integration points and hybrid capacity ratios of wind-solar has significant effect on power system. Therefore, in this paper, the influence of different wind-solar accommodation conditions on the low frequency oscillation characteristics of power system are analysed based on the IEEE 2-area 4-unit system.

2. Model and control of wind power generation system

Wind turbines convert wind into electrical energy, which is integrated into power grid by controlling a series of converters. The control structure diagram of wind power generation system is shown in figure 1.

![Figure 1. The control structure diagram of wind power generation system.](image1)

The aerodynamic mathematical model of wind turbine can be expressed as:

\[ P_m = \rho C_p(\lambda, \beta) \pi R^2 v^3 / 2 \]  

\[ \lambda = \omega R / v \]  

Where \( P_m \) is the mechanical power of wind turbine; \( \rho \) is air density; \( R \) is the radius of impeller of wind turbine; \( v \) is wind speed; \( \omega \) is the speed of wind turbine; \( \lambda \) is the tip speed ratio; \( \beta \) is the pitch angle; \( C_p \) is the wind energy conversion efficiency coefficient of blade, and it is a function of \( \lambda \) and \( \beta \). When the pitch angle \( \beta \) keeps unchanged and the tip speed ratio \( \lambda \) reaches the maximum value, the wind energy conversion efficiency coefficient \( C_p \) will reach its maximum value too.

The 4th order mathematical model of DFIG (Doubly Fed Induction Generator) in \( d-q \) coordinate axis can be referred to reference [2].

3. Model and control of photovoltaic power generation system

In photovoltaic power generation system, the photovoltaic cells are connected in series and parallel to build up the photovoltaic array model. The photovoltaic array, power controllers and other components jointly compose the photovoltaic power generation device. Photovoltaic array can directly convert sunlight into electrical energy, which can be used by users or connected to power grid. The control structure diagram of photovoltaic power generation system is shown in figure 2.

![Figure 2. The control structure diagram of photovoltaic power generation system.](image2)

The \( U-I \) equation of photovoltaic array can be expressed as:

\[ I = n_p I_{ph} - n_p I_0 \left( e^{(U+IR_s)/n_snkT} - 1 \right) \]  

Where \( I \) and \( U \) are the output current and voltage of photovoltaic array respectively; \( I_{ph} \) is photocurrent; \( I_0 \) is reverse saturation current of diode; \( R_s \) is the series resistance of photovoltaic module; \( n_p \) and \( n_s \) are the number of parallel and series modules of photovoltaic array respectively; \( q \) is electronic charge; \( k \) is Boltzmann constant; \( T \) is absolute temperature; \( n \) is ideal factor of photovoltaic cell.
4. Model and control of wind-solar hybrid generation system
The wind-solar hybrid generation system consists of wind power generation system and photovoltaic power generation system. The electrical energy generated by wind farm and photovoltaic array is integrated into power grid after a series of boost converters. The control structure diagram of the grid-connected wind-solar hybrid generation system is shown in figure 3.

There are three operating states of wind-solar hybrid generation system: (1) only with wind farm power generation in the power system; (2) only with photovoltaic array power generation in the power system; (3) both with wind farm and photovoltaic array power generation in the power system. The operating state of the wind-solar hybrid generation system is affected by wind speed, solar intensity, load consumption and discharge capacity of the energy storage device, and so on, which are random. Therefore, the controller is usually used to make the wind-solar hybrid generation system in the optimal working state. The functions of the controller mainly include the following aspects: (1) Controlling the output power of wind farm and photovoltaic array; (2) Controlling the charge and discharge state of the energy storage device; (3) Coordinating the control of the input and output of the system; (4) Protecting and monitoring the system.

5. Analysis of low frequency oscillation of power system with different wind-solar hybrid system

5.1. Effect of wind-solar separate integration on the damping characteristics of power system
The IEEE 2-area 4-unit interconnection system shown in figure 4 is constructed under MATLAB/Simulink based PSAT. The interconnection system consists of two similar areas connected by a contact line. Each area has two tightly coupled units. The reference capacity is 100MVA and the frequency is 50Hz. For ease of analysis, this paper uses the single model of wind turbine to replace the entire wind farm, and the single model of photovoltaic to replace the entire photovoltaic array. Detailed parameters can be referred to reference [3].

In order to analyse the damping characteristics of interconnected system when wind-solar are separately integrated, the eigenvalue analysis is mainly adopted to study the following three operating conditions in this section:
- **Case1**: Without wind farm and photovoltaic array.
- **Case2**: With wind farm only, the output of wind farm is 30MW.
- **Case3**: With photovoltaic array only, the output of photovoltaic array is 30MW.

Partial eigenvalues of the system in above three cases are shown in table 1. It can be seen that the system has three original oscillation modes: mode 1 and mode 2 are both local oscillations of the generators in area 1 or area 2, mode 3 is the interarea oscillation between the generators in area 1 and area 2. The system adds an interarea oscillation mode 4 related to wind farm and photovoltaic array when wind farm and photovoltaic array are integrated into the system. $\zeta_1$ is slightly decreased, $\zeta_2$ and $\zeta_3$ are both increased in case 2 and case 3 compared with these in case 1. In addition, comparing case 2 with case 3, $\zeta_2$ is the same, but $\zeta_1$ is relatively larger in case 2, $\zeta_3$ and $\zeta_4$ are larger in case 3. Therefore, the results show that both the separate integration of wind farm and photovoltaic array can improve the...
stability of the system to a certain extent, and at the same time, there is some complementarity between the two integration conditions.

Table 1. Partial eigenvalues of the system with wind-solar separate integration.

| Case | Mode | Eigenvalue(λ) | Damping ratio(ζ)% | Related units |
|------|------|---------------|-------------------|---------------|
|      |      |               |                   |               |
| Case 1 | | | | |
| 1 | | −0.9835±j6.9109 | 14.09 | G1 G2 |
| 2 | | −1.2060±j7.1952 | 16.53 | G3 G4 |
| 3 | | −0.3025±j4.0377 | 7.47 | G1 G3 |
| Case 2 | | | | |
| 1 | | −0.9833±j6.9126 | 14.08 | G1 G2 |
| 2 | | −1.2443±j7.1739 | 17.09 | G3 G4 |
| 3 | | −0.3096±j4.0433 | 7.65 | G1 G3 |
| Case 3 | | | | |
| 1 | | −0.9759±j6.9141 | 13.98 | G1 G2 |
| 2 | | −1.2443±j7.1737 | 17.09 | G3 G4 |
| 3 | | −0.3161±j4.0245 | 7.83 | G1 G3 |
| 4 | | −0.3452±j0.6883 | 44.83 | G1-G4, PV |

Table 2. Partial eigenvalues of the system under different integration points.

| Case | Mode | Eigenvalue(λ) | Damping ratio(ζ)% | Related units |
|------|------|---------------|-------------------|---------------|
|      |      |               |                   |               |
| Case 4 | | | | |
| 1 | | −0.9835±j6.9109 | 14.09 | G1 G2 |
| Case 5 | | | | |
| 1 | | −0.9833±j6.9126 | 14.08 | G1 G2 |
| 2 | | −1.2443±j7.1739 | 17.09 | G3 G4 |
| 3 | | −0.3096±j4.0433 | 7.65 | G1 G3 |
| Case 6 | | | | |
| 1 | | −0.9759±j6.9141 | 13.98 | G1 G2 |
| 2 | | −1.2443±j7.1737 | 17.09 | G3 G4 |
| 3 | | −0.3161±j4.0245 | 7.83 | G1 G3 |
| 4 | | −0.3452±j0.6883 | 44.83 | G1-G4, PV |

5.2. Effect of different integration points on the damping characteristics of power system

In order to analyse the damping characteristics when the interconnected system consumes new energy at different integration points, this section mainly focuses on the following operating conditions by adopting eigenvalue analysis, small disturbance analysis and three-phase short-circuit analysis:

Case 4: Without wind farm and photovoltaic array.

Case 5: With wind farm and photovoltaic array in area 1. The output of wind farm is 30MW and the output of photovoltaic array is 40MW.

Case 6: With wind farm in area 1, with photovoltaic array in area 2. The output of wind farm is 30MW and the output of photovoltaic array is 40MW.

Partial eigenvalues of the system in above three cases are shown in table 2. The difference of wind-solar integration point has a certain influence on the damping oscillation of the system. Compared with case 4, ζ1 is decreasing, ζ2 and ζ3 are both increased in case 5. ζ1, ζ2 and ζ3 are all increased in case 6. What’s more, only ζ2 is slightly decreased, ζ1, ζ2 and ζ3 are all increased in case 6 compared with these in case 5. Therefore, the results show that the system is more stable when wind farm and photovoltaic array are integrated into transmitting side and receiving side respectively.

Assuming that the load on bus7 fluctuates upward by 10% during the period of 1.0s-1.05s, the simulation time is 20s, and the frequency is 50Hz. The time-domain simulation of δG1 and Vbus0 for different integration points under small disturbance condition is shown in figure 5. In addition, assuming that the double-circuit line 8-9 of interconnected system is three-phase short-circuit grounded when time is 1.0s, the fault is eliminated when time is 1.05s. The simulation time is 20s and the frequency is 50Hz. The time-domain simulation of δG2 and Vbus11 for different integration points under three-phase short-circuit condition is shown in figure 6.

According to three integration conditions, it can be seen from figure 5 that the stable time and amplitude of δG1 are not changed much. But the stable time and amplitude of Vbus0 are both smaller in case 6 than these in case 5. What’s more, it’s not hard to see from figure 6 that the stable time and amplitude of δG2 are not changed much in three cases. But the amplitude of Vbus11 is the smallest and the stable time is relatively shorter in case 6. Therefore, the simulation results show that the system is more likely to be stable when wind farm and photovoltaic array are integrated into transmitting side and receiving side respectively.
With the increase of the output of wind farm and photovoltaic array, the interarea oscillation characteristics of power system are analysed based on IEEE 2-area 4-unit system. The disturbance condition is shown in figure 7. The time-domain simulation of interarea oscillation that wind-solar hybrid capacity ratio affects the stability of wind-solar hybrid generation system.

5.3. Effect of different wind-solar hybrid capacities on the damping characteristics of power system

This section analyses the influence of different wind-solar hybrid capacities on the damping characteristics of the system when wind farm and photovoltaic array are integrated into transmitting side and receiving side respectively. The capacity ratios are:

Case 7: The output of wind farm is 10MW, and the output of photovoltaic array is 30MW.
Case 8: The output of wind farm is 30MW, and the output of photovoltaic array is 40MW.
Case 9: The output of wind farm is 75MW, and the output of photovoltaic array is 75MW.

By adopting eigenvalue analysis to the above three cases, the following conclusions can be drawn: With the increase of the output of wind farm and photovoltaic array, $\zeta_1$, $\zeta_2$ and $\zeta_3$ are increased, but the interarea oscillation $\zeta_4$ associated with wind farm and photovoltaic array is reduced. The results show that wind-solar hybrid capacity ratio affects the stability of wind-solar hybrid generation system.

The time-domain simulation of $\delta_{G1}$ and $V_{bus03}$ for different wind-solar hybrid capacities under small disturbance condition is shown in figure 7. The time-domain simulation of $\delta_{G2}$ and $V_{bus09}$ for different wind-solar hybrid capacities under three-phase short-circuit condition is shown in figure 8.

Under three capacity ratios, it can be seen from figure 7 that the amplitude of $\delta_{G1}$ and $V_{bus03}$ are the smallest, and the stable time of $V_{bus03}$ is the shortest in case 7. What’s more, it’s not hard to see from figure 8 that the amplitude of $\delta_{G2}$ and $V_{bus09}$ are the smallest. And at the same time, the stable time of $V_{bus09}$ is the shortest in case 7. Therefore, the simulation results show that the system is more likely to be stable when the output of wind farm and photovoltaic array are smaller.

6. Conclusion

In this paper, the influence of different wind-solar accommodation conditions on the low frequency oscillation characteristics of power system are analysed based on IEEE 2-area 4-unit system. The results show that: (1) Wind-solar are highly complementary in terms of improving the damping ratio of the system; (2) Compared with that wind farm and photovoltaic array are both integrated into transmitting side, the system is more stable and the damping characteristic is better when wind farm and photovoltaic array are integrated into transmitting side and receiving side respectively; (3) Wind-solar hybrid capacity affects the damping ratio of the oscillation mode of interconnected system.
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References
[1] Wang C L, Liu H, Gong J F, Li J F and Yang S H 2018 Joint scheduling of different energy storage for improving wind power accommodation ability in integrated community energy system J. Electric Power Construction 39 (04) 35-44 (in Chinese)
[2] He P, Wen F S, Ledwich G, Xue Y S and Huang J S 2014 Investigations on the impacts of various types of wind turbine generators on power system stability J. Journal of Energy Engineering 140(02) 1-10
[3] He P, Wen F S, Ledwich G and Xue Y S 2016 An investigation on interarea mode oscillations of interconnected power systems with integrated wind farms J. International Journal of Electrical Power and Energy Systems 78(02) 145-157
[4] Grace S S, Ashok S, and Kumaravel S 2017 Small signal stability analysis of grid connected renewable energy resources with the effect of uncertain wind power penetration Int. Conf. on Power Engineering Computing and Control (PECCON) vol 117, pp 769-776
[5] Remon D, Cantarellas A M, Mauricio J M and Rodriguez P 2017 Power system stability analysis under increasing penetration of photovoltaic power plants with synchronous power controllers J. IET Renewable Power Generation 11(06) 733-741
[6] Eftekharnejad S, Vittal V, Heydt G T, Keel B and Loehr J 2013 Small stability assessment of power systems with increased penetration of photovoltaic generation: a case study J. IEEE Transactions on Power Systems 4(04) 960-967
[7] Eftekharnejad S, Vittal V, Heydt G T, Keelx B and Loehr J 2013 Impact of increased penetration of photovoltaic generation on power systems J. IEEE Transactions on Power Systems 28(02) 893-901
[8] Liu Y, Qin W, Han X and Wang P 2017 Modelling of large-scale wind/solar hybrid system and influence analysis on power system transient voltage stability Conf. on Industrial Electronics and Applications (ICIEA) (Siem Reap) pp 477-482
[9] Choudhary S and Sharma F B 2015 Small signal stability analysis of renewable source connected power system and identification of oscillatory modes using wavelet transform Int. Conf. on Smart Grid and Clean Energy Technologies (ICSGCE) (Offenburg) pp 23-29
[10] Li G L 2016 Large-scale hybrid wind solar systems modelling and voltage stability analysis of power system D. Taiyuan University of Technology (in Chinese)
[11] Sohan C and Sumit P 2015 Influence of grid connected solar and wind energy on small signal stability Int. Conf. on Technological Advancements in Power and Energy (TAP Energy) (Kollam) pp 23-28