

Rotation Speed Recovery Strategy Based On Particle Swarm Optimization for Variable Power Curve Optimization

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Abstract: With the increase of wind power capacity incorporated into the grid, the permeability of wind power increases continuously, which leads to the reduction of the equivalent inertia of the system. Rotor speed recovery will cause the secondary frequency dips when DFIG uses rotor inertial control to participate in system frequency modulation. In order to optimize the secondary frequency dips, this paper uses PSO (Particle Swarm Optimization) to optimize the Parameters of Variable Power Functions on the basis of the previously proposed variable power curve strategy. This article simulates this strategy through setting up a system by Simulink. Simulate the results of optimization, compared with the traditional recovery strategy, validity of the proposed strategy is demonstrated through simulation and analysis.

1. Introduction

Assuming that DFIG uses rotor inertial control to participate in grid frequency modulation, the rotor would release the kinetic energy stored in rotor of the wind turbine for the purpose of frequency support when the system frequency decreases, which leads to a continuous drop of the rotor speed. When the rotor speed reaches the lower speed limit, the wind turbine must exit frequency modulation, as a result, the output power drops suddenly causing the secondary dips of the system frequency. Domestic and overseas scholars have made a large number of researches on frequency regulation of wind turbines in the power system. Through modelling the mathematical models of frequency modulation process of the wind turbine, the literature [1] seeks the optimal exit equation group which can optimize the problem of the secondary frequency dips from the perspective of the moment of exiting the frequency modulation. But the calculation volume is too large to be applied to engineering operations. The literature [2, 3] continuously corrects the coefficients of the power tracking curve online, avoiding the direct drop of the active power output to the MPPT and reducing the secondary dips of the frequency when the wind turbine exits the frequency modulation. However, this method is difficult to operate which is usually no way to apply in the project. In literature [4], after exiting the



frequency modulation, the electromagnetic power is kept linearly decreasing with time to prevent the frequency from falling for the second times. In the literature [5], the reference speed is controlled to recover in a step-like manner to avoid the secondary dips caused by the rapid recovery of the rotational speed which means the rotor speed decrease continuously during the frequency regulation. In paper [6, 7], a new method has been proposed which uses fixed acceleration torque and PI controller to recovery the rotor speed respectively and improve the smoothness of the mode switching as well as the secondary frequency dips. But it needs to change the parameters in real time, and it is not easy to realize in project because of the complex operation. In article [8], an extended state observer is applied to estimate the input mechanical power of the wind turbine in real time. Based on this, a given curve of electromagnetic power is designed to improve the secondary frequency dips. However, the design criterion of the power curve is not given, which is not easy to achieve in engineering. In this paper, based on the design of the electromagnetic power curve of the speed recovery stage, the parameters of the variable power function are optimized by using the particle swarm algorithm, and the best value for minimizing the secondary drop of frequency is found in the local area.

2. Rotation Speed Recovery Strategy Based On Variable Power Curve of Inertia Control from DFIG Wind Turbine

2.1. Working principle

In the process of recovering the rotor speed with MPPT strategy, the sudden drop of the active power output of the wind turbine causes the secondary dips of the grid frequency. In order to optimize the secondary dips, a new speed recovery strategy based on the variable power curve is proposed formerly in this paper. This strategy is mainly designed to change the power curve that make the active power decrease gradually, so as to achieve the purpose of optimizing the secondary dips. The structure of the proposed strategy is shown in Figure 1.

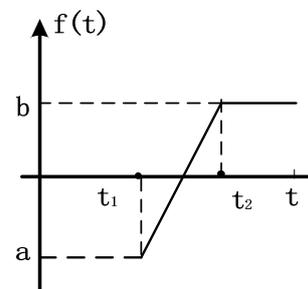
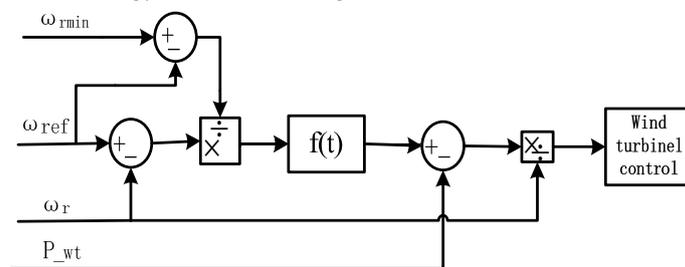


Figure 1. The structure of the proposed speed recovery strategy.

Figure 2. The image of the variable power function $f(t)$.

In Figure 1, ω_{ref} presents the reference value of the rotor speed, and ω_{rmin} is the lower limit speed of the DFIG when it participates in frequency-modulation. $f(t)$ is a variable power function, it is a human-set function, and the expression of the variable power curve P_{ac} of the strategy is:

$$P_{ac} = f(t) \cdot \frac{\omega_{ref} - \omega_r}{\omega_{ref} - \omega_{rmin}} \quad [8] \quad (1)$$

The wind turbine would withdraw from the frequency regulation once the rotor speed ω_r drops to the lower speed limit ω_{rmin} . Set the coefficient of the variable power curve $\frac{\omega_{ref} - \omega_r}{\omega_{ref} - \omega_{rmin}}$ to avoid the

output electromagnetic power of wind turbine dropping too much at the beginning of the exiting of frequency regulation. During the recovery phase, the rotor speed ω_r restores to ω_{ref} and the variable power curve coefficient reduces from 1 to 0 gradually.

2.2. Variable power curve and its design

The image of the variable power function $f(t)$ is shown in the figure 2, where t_1 is the time of exiting the frequency regulation, and t_2 is the time when the variable power function reaches the maximum value. After t_2 , $f(t)$ remains unchanged.

3. The algorithm of Particle Swarm Optimization and its optimizing steps

The PSO algorithm was originally designed to graphically simulate the beautiful and unpredictable movement of a flock of birds. By observing the social behaviour of animals, people found that sharing information in groups facilitates the advantage in evolution, based on which the PSO algorithm has been developed. Shi et al. further introduced the inertia weight to form the current conventional particle swarm algorithm^[9]. Similar to the gradient descent algorithm, the particles follow the optimal particle in the solution space, so that each particle moves in the optimal direction of fitness.

3.1. PSO algorithm optimization steps

PSO algorithm optimization specific steps are as follows:

Step 1, based on the optimization objectives, establish a model in which the DFIG wind turbine participates in the system frequency modulation, initialize the parameters in the variable power function, and establish the optimal boundary conditions.

Step 2, set the weight parameters $c1$ and $c2$ that reflect the cognition ability of the particle itself and the cognition ability of the social experience, which can be set to 1; set the inertia weight parameter $\omega \in [0, 1]$ of the particle to maintain the existing optimization speed, Usually can be set to 0.6; search target search space is equal to 3, according to the empirical definition of space optimization S_n ; define the number of particles is 100, and randomly generate the particle's initial optimization speed $v_i(0)$; set the search for optimization The maximum number of iterations is 100.

Step 3, insert each particle into the model for simulation. Judge whether the constraint condition is satisfied, if satisfied, go to step 4; if not, go to step 7.

Step 4, according to the fitness function, calculate the current fitness value of each particle $fit_i(n)$.

Step 5, if $fit_i(n) > fit_i$, update the particle fitness value, otherwise keep the fitness value unchanged, and record the optimal space position of each particle until the n -th iterations.

Step 6, if $\max[fit_i] > Fit$, $Fit = \min[fit_i]$, and update the globally optimal particle, otherwise keep Fit and xg unchanged, where xg is the global optimum based on active search up to the n -th iteration.

Step 7, calculate the spatial position of particles in the $n + 1$ iterations using the particle velocity and displacement update formula, as shown in equations (2) and (3), $\text{rand}(1)$ is a random number uniformly distributed in the interval $[0, 1]$.

$$V_{id}^{n+1} = WV_{id}^n + c1\text{rand}(1)(P_{id}^n - X_{id}^n) + c2\text{rand}(1)(P_{gd}^n - X_{id}^n) \quad (2)$$

$$X_{id}^{n+1} = X_{id}^n + V_{id}^{n+1} \quad (3)$$

3.2. Fitness function

The optimization goal chosen in this paper is to minimize the frequency drop, that is, from the moment of quitting the frequency modulation, the drop of the grid frequency is minimum in the speed recovery phase:

$$J = \text{MAX}(f_{min}) \quad (4)$$

3.3. PSO parameters setting

The specific parameters of the PSO algorithm are set as follows: particle swarm size $M=100$, maximum iteration number $k=100$, dimension $D=3$, inertia factor $\omega=0.6$, acceleration constant $c_1=1$, $c_2=1$, parameter optimization range is as follows. The results of optimization is $a=-0.04$, $b=0.15$ and $t_2=230$.

$$-0.07 \leq a \leq -0.06 \quad (5)$$

$$0.1 \leq b \leq 0.3 \quad (6)$$

$$220 \leq t_2 \leq 230 \quad (7)$$

4. Simulation analysis

4.1. Construction of simulation system

A wind power system simulation model has been built which includes both of virtual and conventional synchronous units to simulate the secondary dips of wind power virtual synchronous machine based on rotor inertial control strategy. The proposed variable power curve recovery method has been studied and verified comparing with the classic MPPT recovery method.

Firstly, building a wind power system simulation model first which includes both of virtual synchronous generator (2MW/690V x 31) and conventional synchronous generator (250MVA/13.8kV). The structure of the system is shown in Figure 3 of which main parameters are given in Tables 1 and 2 [11].

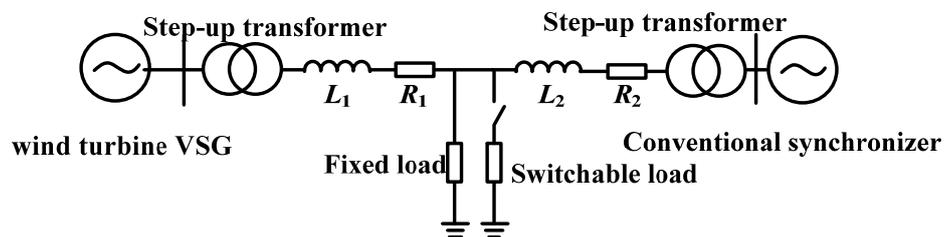


Figure 3. Topology diagram of simulation system.

Table 1. Main parameters of normal synchronous generator

Inertia constant /s	5	drum heat storage volume time constant /s	300
frequency regulation coefficient	15	Super heater volume time constant /s	10
Load frequency modulation coefficient	2	boiler fuel release time constant /s	10
One frequency regulation limited amplitude	3.5%	combustion release delay /s	20
Main steam pressure pipe flow coefficient	3	drum heat storage volume time constant /s	300

Table 2. Main parameters of wind turbine VSG

Inertia constant /s	5.005	inertial frequency regulation coefficient	5
Primary frequency regulation coefficient	20	frequency regulation speed lower limit /pu	0.83

By the end of 2016, the proportion of new energy machine assembly capacity in the regional power grids such as the Northwest Power Grid and North China Power Grid has reached about 20% [10]. In the event of grid frequency disturbances that have occurred in recent years, the maximum power shortage is about 4% [11-12]. Therefore, in the simulation, wind power accounts for about 20% of the installed capacity of the system and power shortage of 4% of the system capacity occurs in the power grid.

4.2. The Simulation of Optimal Results Based on MPPT Curve and Particle Swarm Optimization

In the engineering, the MPPT-based speed recovery strategy is generally used. The method is simple and practical. When the wind turbine speed drops to the lower limit of the speed (0.83 pu), compared with MPPT strategy recovery speed and particle swarm optimization results of this paper, frequency simulation The comparison chart is shown in Figure 4.

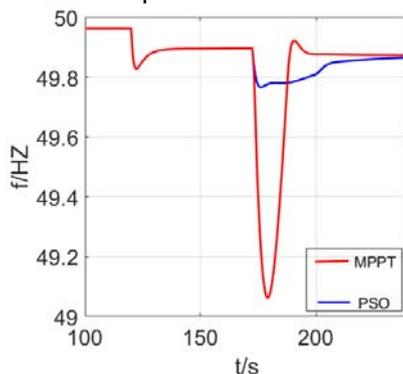
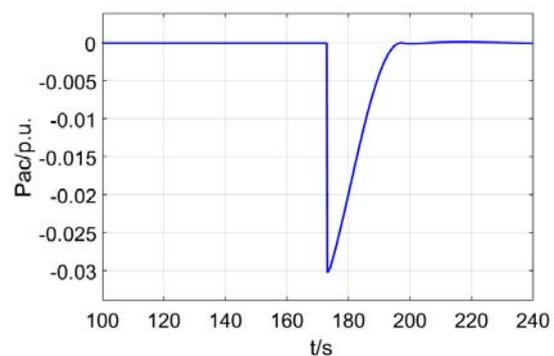


Figure 4. The contrast diagram of the frequency variation.

Figure 5. The image of the variable power curve $f(t)$.

It can be seen from Figure 4 that the strategy of changing the power curve for speed recovery proposed in this paper significantly reduces the depth of the second drop. At this time, the variable power curve P_{ac} is shown in Figure 5.

As shown in Fig. 5, at 173s, the wind turbine speed ω_r drops to the lower speed limit (0.83p.u.), and the wind turbine exits the frequency modulation. The variable power curve P_{ac} gradually changes from negative to zero, and the wind turbine's output electromagnetic power gradually drops to the initial value. The following compares the output electromagnetic power of two speed recovery strategies, as shown in Figure 6.

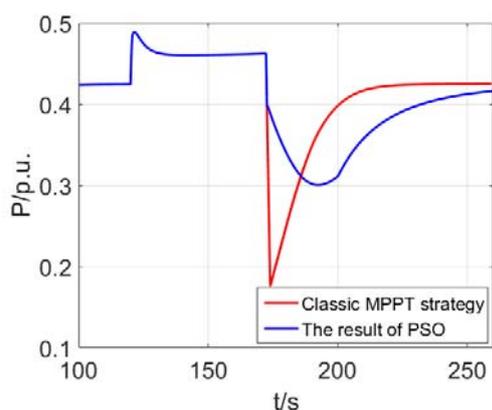


Figure 6. The contrast diagram of the power variation.

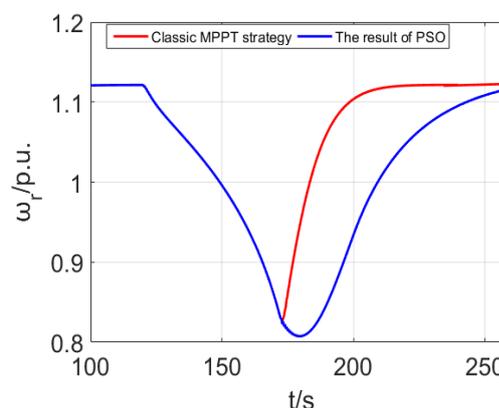


Figure 7. The contrast diagram of the rotor speed variation.

It can be seen from Figure 8 that when the wind turbine exits the frequency modulation, the electromagnetic power output under the variable power curve strategy proposed in this paper gradually decreases, and when using the classic MPPT strategy to recover the speed, it will cause the output to be reduced to the lowest value. Caused a second dip. The following compares the speed changes of two speed recovery strategies, as shown in Figure 7.

As can be seen from Figure 7, at 173s, the wind turbine speed ω_r drops to the lower speed limit (0.83 pu), the wind turbine exits the frequency modulation, when the particle swarm optimization algorithm is used to optimize the speed recovery, the speed will not immediately recover when the output electromagnetic power. Below the mechanical power, the speed is restored. Obviously, using the variable power curve for speed recovery reduces the secondary drop of the system frequency, but the speed recovery time is long.

5. Conclusion

In recent years, the cumulative installed capacity of wind power in China has increased rapidly, and the penetration rate of wind power continues to increase. The instability of wind power has had threaten to the safety of power systems. DFIG causes the secondary dips of frequency when rotor inertia control is applied to frequency regulation. In this paper, particle swarm optimization algorithm is used to optimize the parameters of the variable power function to reduce the drop of the active power output, so as to reduce the secondary dips of frequency caused by the sudden drop of the active power output during the speed recovery phase. There are still some deficiencies in this article. At the moment of exiting frequency modulation, the change of electromagnetic power is not smooth enough, and it needs to be optimized continuously. For example, to improve the secondary dips, the combination of energy storage system and wind power system should be applied, as well as a multi-machine coordinated control strategy. In addition, the model predictive control theory can be applied to wind power frequency regulation which can achieve accurate tracking of frequency, power and speed, so as to achieve the purpose of reducing secondary dips.

Acknowledgments

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References

- [1] X.Wang, W.Du. Virtual inertia control of grid-connected wind farms[J]
- [2] Liu Zhiwind turbine, Optimal termination time of inertia control from DFIG wind turbine.[D]. Master's thesis of Shandong University.2017

- [3] Li Licheng ,Ye Lin.Coordinated Control of Frequency and Rotational Speed for Direct Drive Permanent Magnet Synchronous Generator Wind Turbine at Variable Wind Speeds.[J]. Automation of Electric Power Systems,2011,35(17) :26-31
- [4] LIU Zhangwei, LIU Feng, MEI Shengwei, et al. Application of extended observer in wind turbines speed recovery after inertia response control[J]. Proceedings of the CSEE, 2016, 36(5): 1207-1217
- [5] Wu Ziping,Gao Wenzhong,Wang Jianhui,etal.Acoordinated Primary Frequency Regulation from Permanent Magnet Synchronous Wind Turbine Generation [C]//IEEE in Power Electronics and Machines in Wind Applications(PEM-WA).Denver,Co,USA:IEEEPress,2012:1-6
- [6] Erlich I, Wilch M. Primary frequency control by wind turbines[C]// Power and Energy Society General Meeting. IEEE, 2010:1-8
- [7] Yuan G Y, Lei Z, Wang M J, et al. Synthesis and characterization of a cadmium(II)–organic supramolecular coordination compound based on the multifunctional 2-amino-5-sulfobenzoic acid ligand[J]. Acta Crystallogr C Struct Chem, 2016, 72(12):939-946.
- [8] Liu Z, Feng L, Mei S, et al. Application of Extended State Observer in Wind Turbines Speed Recovery After Inertia Response Control[J]. Proceedings of the Csee, 2016
- [9] Shi Y, Eberhart R. Modified particle swarm optimizer[C]// Proc. of IEEE ICEC conference, Anchorage. 1998:69-73.
- [10] SHU Yinbiao, ZHANG Zhigang, GUO Jianbo, et al. Study on key factors and solution of renewable energy accommodation[J]. Proceedings of the CSEE, 2017, 37(1): 1-8
- [11] LI Zhaowei, WU Xuelian, ZHUANG Kanqin, et al. Analysis and reflection on frequency characteristics of east China grid after bipolar locking of “9.19” jinping-sunan DC transmission line[J]. Automation of Electric Power Systems, 2017, 41(7): 149-155.
- [12] MA Jin, ZHAO Dawei, QIAN Minhui, et al. Reviews of control technologies of large-scale renewable energy connected to weakly-synchronized sending-end dc power grid[J]. Power System Technology, 2017, 41(10): 3112-3120