Parameters tuning of doubly fed induction generator systems with static synchronous compensator based on Chaos orthogonal particle swarm optimization

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Abstract. For Double-Fed Induction Generator (DFIG) wind farm systems with Static Synchronous Compensator (STATCOM), by optimizing multiple proportional integral (PI) controllers parameters of DFIG and STATCOM, the performance of the wind power system is significantly improved and the voltage of point of common coupling (PCC) is quickly restored when a low voltage due to a grid fault. Chaos orthogonal particle swarm optimization is proposed to make the integral time absolute error (ITAE) of active power of DFIG, DC-link voltage of converter of DFIG and voltage of PCC minimum. The orthogonal method is used to get the range of parameters and identify the weight relations between different indicators. And then the chaos algorithm is used to initialize the algorithm. Finally, the particle swarm optimization (PSO) can effectively improve the efficiency of the optimization. Based on MATLAB/Simulink, the simulations of wind farm containing STATCOM incorporated into the infinite system under different conditions both show that the application optimized PI controllers have good dynamic performance, which validates the effectiveness of the optimization algorithm.

1. Introduction

Compared with the traditional fossil energy, as a clean energy, wind power has been brought into sharp focus due to its advantages of pollution-free, emission free and green environmental protection. Doubly fed induction generator (DFIG) [1,2] is one of the main types of wind farm. Static Synchronous Compensator (STATCOM) as a reactive power compensation device can effectively improve the voltage fluctuation of the wind power grid [3-5]. Now general wind farm is equipped with STATCOM. The design of PI controller parameters directly affects the control performance of STATCOM. From an external perspective, DFIG and STATCOM as a whole respond to dynamic changes of system. In order to obtain good output characteristics, it is necessary to consider the optimization of multiple PI controller parameters of both. The optimization methods for the parameters of PI controller mainly include the traditional adjustment trial method [6], approximate linearization method [7] and intelligent optimization algorithm [8-14]. Recent years, with the rapid development of intelligent algorithms, more and more research has been done on the optimization of PI controller parameters using intelligent algorithms, such as Particle Swarm Optimization (PSO) [15-

19]. In [16], PSO algorithm was introduced for parameter optimization, and time-domain performance criteria were used to optimize parameters of proportional integral derivative (PID) controllers. In [17], an improved PSO algorithm based on the d-tent chaotic model was proposed. By modifying the inertial weight of the globally optimal particle and introducing the d-tent chaotic sequence, the convergence speed of the algorithm was improved. In [18], a fuzzy PI Model Reference Adaptive System (MRAS) observer is proposed. The fuzzy PI controller is applied to the MRAS observer, and the PI coefficient is adjusted by the fuzzy controller, so that the PI controller has good dynamic stability in the wide speed range. The improved PSO algorithm is proposed to optimize the PI parameters of the DFIG control system in [19], and the problem of parameter optimization in complex systems with multiple inputs and outputs is solved. These above improved PSO algorithms have 3 points to be improved. First of all, the rapid convergence of the algorithm can be achieved by increasing the initial value quality or quickly determining the optimization range and optimization direction of each controller parameter, but the existing improved PSO algorithm rarely takes care of these two points. Then, the optimization object only includes the PI controller parameters of DFIG, without considering the value of the PI controller parameter of STATCOM in the wind farm. Finally, the simulation example only verifies the effectiveness of the parameter optimization algorithm under fixed conditions, without considering the practicality of the algorithm if the operating conditions change in the actual situation.

In view of the above 3 points, this paper proposes a new method by tuning parameters of DFIG Systems with STATCOM for wind turbines based on chaos orthogonal particle swarm optimization. This algorithm combines the advantages of chaos algorithm and orthogonal particle swarm optimization, which can improve the quality of initial value, quickly determine the range and direction of optimization, as well as reduce the number of iterations. As the optimization objective function, the integral time absolute error (ITAE) of active power of DFIG, direct current (DC)-link voltage of converter of DFIG and voltage of point of common coupling (PCC) should be minimized. This method takes into account both the output characteristics of the DFIG power generation system and the STATCOM adjustment characteristics and improves the overall dynamic performance of the wind farm. At last, under the two different operating conditions, by taking the wind farm with STATCOM into the infinity system as an example, the effectiveness of the proposed algorithm is verified by MATLAB / Simulink simulation.

2. DFIG wind power generation control system with STATCOM

The overall structure of DFIG wind power generation system with STATCOM used in this paper is shown in figure 1. The stator side of the wind turbine is directly connected to the grid, and the rotor side is connected to the grid through a back-to-back PWM converter (including grid side converter (GSC) and rotor side converter (RSC)), and the STATCOM is installed at the PCC point. STATCOM is connected to the power grid through a reactor. In figure 1, R and L are the equivalent resistance and inductance of the connected reactor. U_{PCC} is the common connection point voltage of the DFIG wind turbine and STATCOM connected to the grid.

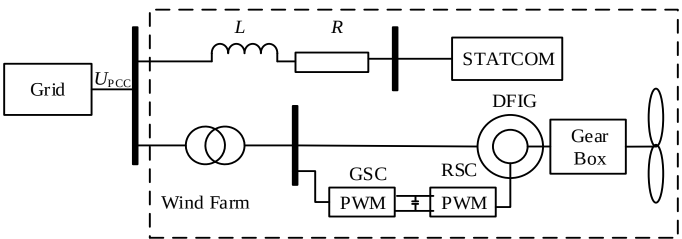

Figure 1. Wind power generation system with STATCOM.

2.1. The control of DFIG

The main function of the GSC in the DFIG alternating current (AC) excitation converter is to maintain the stability of the DC bus voltage. The vector control strategy is based on grid voltage, and the control model is shown in figure 2 [20,21]. In figure 2, u_{rd} is the d axis component of the grid voltage, i_{rd} is the d axis component of input current and U_{dc} is the DC bus voltage. All superscript * values are reference values. The subscript s represents a value on the rotor and the subscript r represents a value on the stator. K_{p1}, K_{i1}, K_{p2}, K_{i2} are the PI controller parameters of the network side voltage outer loop and current inner loop of the DFIG.

The main function of RSC in DFIG AC excitation converter is power control. The control strategy is based on stator magnetic chain. The profile of the rotor side control is shown in figure 3 [21,22]. Where, P_s is the active power of stator output, Ψ is stator flux linkage, L_m is the equivalent mutual inductance between stator windings and stator windings, and L_s is self-inductance between stator windings. K_{p3}, K_{i3}, K_{p4} and K_{i4} are PI controller parameters of active power outer loop and current inner loop of the DFIG.

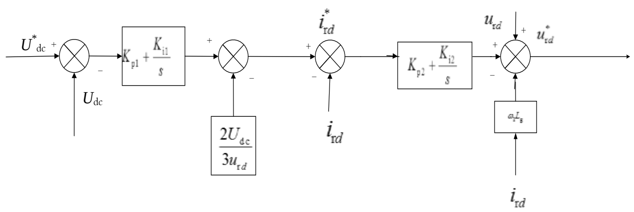

Figure 2. Grid side vector control system.

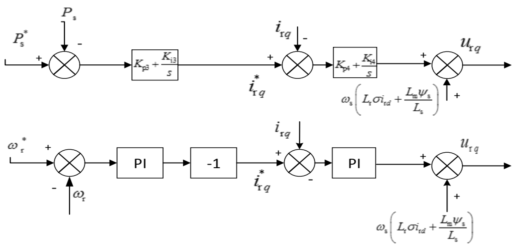

Figure 3. Rotor side vector control system.

2.2. The control of STATCOM

The control objective of the STATCOM is to keep the voltage of PCC point constant, so that the DFIG wind generator always keeps the grid connection in the case of voltage sag. In order to demonstrate the superiority of the optimization algorithm presented in this paper, the static compensator STATCOM alone performs reactive power compensation for the power system, and the DFIG does not participate in the coordinated control of the reactive power. The STATCOM control model is shown in figure 4. In figure 4, U_{dc} is the DC voltage, U_{PCC} is the voltage of the PCC, and i_d and i_q are the current of d and q axis respectively. K_{p5}, K_{i5}, K_{p6} and K_{i6} are the PI controller parameters of voltage outer loop and current inner loop of the STATCOM.

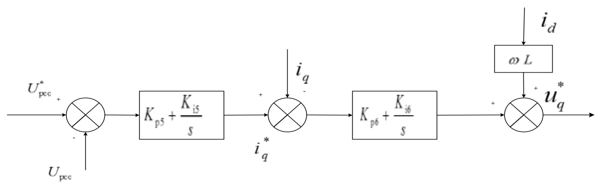

Figure 4. STATCOM control system.

3. Optimization of parameters of multiple PI controller in wind farm

3.1. The objective function

The output characteristic of DFIG wind farm with STATCOM and the voltage of PCC as the performance index are designed according to the ITAE criterion. Individual performance indicators are shown in equations (1), (2) and (3), and the comprehensive performance index is shown in equation (4).

$$J_{P_{s,ITAE}} = \int_0^T t\left|P_s^* - P_s\right| \tag{1}$$

$$J_{U_{\text{dc.ITAE}}} = \int_0^T t\left|U_{\text{dc}}^* - U_{\text{dc}}\right| \tag{2}$$

$$J_{U_{\text{PCC.ITAE}}} = \int_0^T t\left|U_{\text{PCC}}^* - U_{\text{PCC}}\right| \tag{3}$$

$$J' = r_2\left(r_1 J_{P_{\text{s.ITAE}}} + J_{U_{\text{dc.ITAE}}}\right) + J_{U_{\text{PCC.ITAE}}} \tag{4}$$

Where, $P_{\text{s.ITAE}}$ is the active power of DFIG, $U_{\text{dc.ITAE}}$ is the DC voltage of converter of DFIG, $U_{\text{PCC.ITAE}}$ is the voltage of PCC, J represents the ITAE performance index of this item, J' represents a comprehensive performance index, T is the time of dynamic response regulation, r_1 and r_2 are weighting factors and all superscript * values are reference values. The objective function is designed as a two-level nesting pattern as shown in equation (4).

With the above three single performance indexes at the same time as the objective function, chaos algorithm and orthogonal particle swarm optimization algorithm are combined. And then a new algorithm named chaotic orthogonal particle swarm optimization algorithm is proposed to optimize the controller parameters of the DFIG generation system with STATCOM.

3.2. Parameter optimization of Chaos orthogonal particle swarm optimization

3.2.1. The basic principle of traditional particle swarm optimization (PSO) algorithm. The PSO algorithm is an intelligent algorithm that is inspired from the foraging behaviour of animal populations and used to solve planning problems. In the PSO algorithm, the relative merits of the particle is judged by the fitness value and its best position is recorded. At the same time, the best position of the whole group is recorded, as is shown in equation (5).

$$\begin{cases} v_{id} = \omega v_{id} + c_1 p_1\left(p_{id} - x_{id}\right) + c_2 p_2\left(p_{gd} - x_{id}\right) \\ x_{id} = x_{id} + p v_{id} \end{cases} \tag{5}$$

Where, the velocity of a particle is $V_i=(v_{i1},v_{i2},\ldots,v_{iD})$,and its position is $X_i=(x_{i1},x_{i2},\ldots,x_{iD})$. In accordance with the size of the fitness of particles to judge the merits of particles, the local optimal solution is $P_{i\text{best}}=(P_{i1},P_{i2},\ldots,P_{iD})$, and the global optimal solution is $P_{g\text{best}}=(P_{g1},P_{g2},\ldots,P_{gD})$. ω is the inertial weight of the original velocity, c_1 and c_2 are used to balance the global and local optimization capability, which is usually set to 2. p_1 and p_2 are the random Numbers bounded by [0,1]. p is called the constraint factor, which is usually set to 1.

3.2.2. Chaotic orthogonal particle swarm optimization. The traditional PSO algorithm has the following shortcomings in the optimization process:

- The initialization process is random, and the individual quality cannot be guaranteed. Some of the initial particles are far away from the optimal values, thus affecting the efficiency of the iteration.
- There are many parameters in DFIG and STATCOM controllers. The range of each controller parameter is hard to be determined, which increases the difficulty of searching.
- The relationship between each performance index is difficult to coordinate and the weight of each index cannot be determined.

In response to the above three problems, a parameter optimization method based on chaotic orthogonal particle swarm optimization is proposed to hierarchical optimize the controller parameters of STATCOM and DFIG. This method combines the chaos algorithm and orthogonal optimal particle swarm optimization algorithm. That is to say, the optimal range of 12 controller parameters of DFIG and STATCOM and the weighting factors of each performance index are found by using orthogonal optimization method and orthogonal optimal trend method. And then, combined with the randomness of chaotic motion, a large number of groups are generated to improve the quality of the initial value.

Lastly, PSO algorithm is used for iterative optimization. This optimization algorithm can reasonably determine the optimal range and optimization direction of each parameter, as well as the corresponding weight of each performance index. It can also improve the quality of the initial value and effectively reduce the number of iterations.

The main steps of controller parameters optimization based on chaos orthogonal particle swarm optimization are as follows:

- Step 1: Orthogonal experiment and orthogonal optimization trend analysis. The multiple PI controller parameters of the wind farm with STATCOM include 8 parameters of DFIG and 4 parameters of STATCOM. Therefore, the parameters selected by the orthogonal experiment is 12, and each factor selects 7 states. That is, the level is 7. After orthogonal experiments, the effects of $P_{\text{s.ITAE}}$, $U_{\text{dc.ITAE}}$ and $U_{\text{PCC.ITAE}}$ are analysed and the influence of various factors on the experimental indexes is also discussed. The weighting factors r_1 and r_2 can be obtained by equations (6) and (7).

$$r_1 = \frac{\sum_{U_{\text{dc.ITAE}}} \sum_{i=0}^{6} k_{U_{\text{dc}i}}}{\sum_{P_{\text{s.ITAE}}} \sum_{i=0}^{6} k_{P_{si}}} \tag{6}$$

$$r_2 = \frac{\sum_{U_{\text{PCC.ITAE}}} \sum_{i=0}^{6} k_{U_{\text{PCC}i}}}{r_1 \sum_{P_{\text{s.ITAE}}} \sum_{i=0}^{6} k_{P_{si}} + \sum_{U_{\text{dc.ITAE}}} \sum_{i=0}^{6} k_{U_{\text{dc}i}}} \tag{7}$$

Where, $k_{P_{si}}$, $k_{U_{\text{dc}i}}$ and $k_{U_{\text{dc}i}}$ are respectively the values of $P_{\text{s.ITAE}}$, $U_{\text{dc.ITAE}}$ and $U_{\text{PCC.ITAE}}$ corresponding to different levels of each factor in the orthogonal experiment. Through orthogonal experiments, the optimal range of each controller parameter is obtained.

- Step 2: Chaos initialization. According to these 12 parameters, a 12 dimensional random vector (u_i=[u_{01},u_{02},…,u_{12}]) is generated. The value of each dimension fluctuates from 0 to 1.

$$u(k+1) = \mu u(k)(1-u(k)) \tag{8}$$

Through equation (8), N random vectors (u_i (i=1,2,..N)) can be calculated,μ is the control parameter (μ=(0,4]). The 12 components of u_i are divided into 12 controller parameters of wind farm ([K_{p1}, K_{i1}, K_{p2}, K_{i2}, K_{p3}, K_{i3}, K_{p4}, K_{i4}, K_{p5}, K_{i5}, K_{p6}, K_{i6}]). Where, K_{p1}, K_{i1},……, K_{p6}, K_{i6} are the PI controller parameters of the network side voltage outer loop and current inner loop of the DFIG, active power outer loop and current inner loop of the DFIG and voltage outer loop and current inner loop of the STATCOM, respectively. It also generate multiple initial positions (x_i=(x_{i1},x_{i2},…,x_{iN})), with a number of N. The fitness functions of x_i are calculated by equation (4). At the same time, it randomly generates multiple initial speeds, with a number of M. The individual extremum ($P_{i\text{best}}$) and global extremum ($P_{g\text{best}}$) were recorded simultaneously.

- Step 3: Update the $P_{i\text{best}}$ and global $P_{g\text{best}}$ of each particle.
- Step 4: particle update. Update the position and velocity of particles according to equation (5).
- Step 5: Check whether the end conditions are met. Whether the number of loops reaches the set value, output P_{gbest}, otherwise go to step 3.

4. Simulation results

The example system is built with MATLAB/Simulink to verify the correctness and effectiveness of the chaotic orthogonal particle swarm optimization algorithm, which is a wind power system with 6 wind turbines connected. And PCC points in parallel with STATCOM. The rated power of each wind turbine is 1.667 MW. Assuming that the system fails at time t = 0.15 s, the system voltage will generate a small disturbance, dropping to 0.9 pu. The fault lasts 0.1 s and it is cut off at 0.25 s. The whole simulation is divided into the following two parts.

4.1. Performance simulation of wind farm with STATCOM under fixed condition
Orthogonal experiments were performed on $P_{\mathrm{s.ITAE}}$, $U_{\mathrm{dc.ITAE}}$ and $U_{\mathrm{PCC.ITAE}}$ by using (6) and (7) to obtain the two weight factors r_1=67.176, r_2=2.387. Equations (9) and (10) are the optimal ranges of controller parameters for particle swarm optimization.

$$U_{\mathrm{p}} = [60, 700, 10, 20, 10, 5, 3, 60, 0.8, 2600, 0.9, 250] \tag{9}$$

$$L_{\mathrm{p}} = [0, 100, 0, 0, 0, 0, 0.1, 3, 0, 2400, 0, 110] \tag{10}$$

Where U_{P} is the upper limit and L_{p} is the lower limit.

Based on the randomness, ergodicity and regularity of chaotic motion, a large number of initial populations generated by these 12 parameters are initialized by chaos algorithm. In the optimization process, the adaptive value change curve of ordinary PSO algorithm and chaotic orthogonal particle swarm algorithm is shown in figure 5. When the maximum number of iterations is set to 20 times, compared with the ordinary PSO algorithm, the chaotic orthogonal particle swarm algorithm converges faster. The solution efficiency is obviously improved.

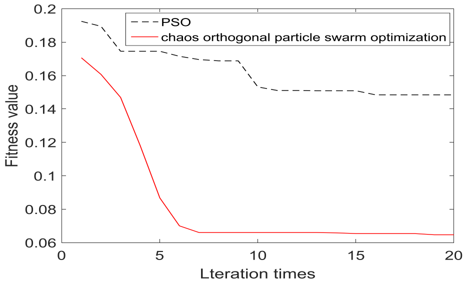

Figure 5. Curve of convergence.

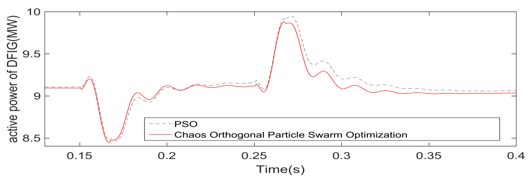

Figure 6. Active power comparison of the two methods.

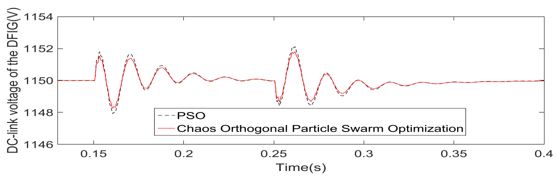

Figure 7. DC bus voltage comparison of the two methods.

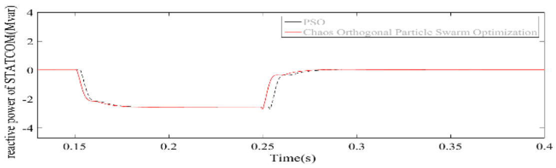

Figure 8. Comparison of reactive power of the STATCOM.

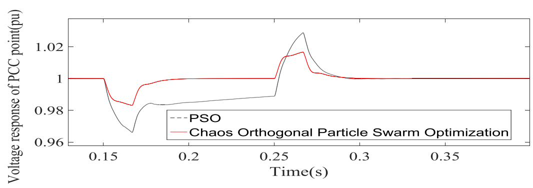

Figure 9. Voltage at the point of common coupling comparison of two methods.

Equation (11) is the final result of the controller parameters obtained by equation (4).

$$[K_{\mathrm{p1}}, K_{\mathrm{i1}}, K_{\mathrm{p2}}, K_{\mathrm{i2}}, K_{\mathrm{p3}}, K_{\mathrm{i3}}, K_{\mathrm{p4}}, K_{\mathrm{i4}}, K_{\mathrm{p5}}, K_{\mathrm{i5}}, K_{\mathrm{p6}}, K_{\mathrm{i6}}] = [49.67, 587.09, 7.68, 0.43, 1.37, 2.36, 0.57, 3, 0.55, 2460, 0.87, 197] \tag{11}$$

In figures 6-9, for the wind farms with STATCOM under fixed condition, the active power, DC bus voltage of the DFIG, reactive power output of STATCOM and the voltage of PCC are compared in the two different algorithms, which are the chaotic orthogonal particle swarm optimization and the ordinary PSO algorithm.

It can be seen from figures 6 and 7 that, compared with ordinary PSO algorithm, when the voltage drops to 0.9pu, the overshoot of the generator stator active power and the DC bus voltage decreases, and so is the fluctuation. As can be seen from figures 8 and 9, whatever using chaotic orthogonal particle swarm algorithm or ordinary PSO algorithm, STATCOM can respond normally and provide reactive support quickly during failure. However, with the chaotic orthogonal particle swarm optimization, the response speed and overregulation of the controller is significantly better than that of the ordinary PSO algorithm, and the voltage of the PCC point has better compensation effect. These verify that the chaotic orthogonal particle swarm algorithm can effectively enhance the anti-perturbation of the system and improve its dynamic performance.

4.2. Performance simulation of wind farm with STATCOM after working condition changes

In the actual situation, various uncertain natural factors or human factors may cause the fixed equivalent electrical parameters of the system to change, thereby affecting the performance of the controllers. In order to verify that the chaotic orthogonal particle swarm optimization has good parameter coordination performance and adaptability, the equivalent inductance of the STATCOM connection reactor is changed from 0.8 mH to 1.6 mH. The rest of the simulation conditions are exactly the same as in the fixed conditions. In figure 10-12, for the wind farms with STATCOM after the change of the working condition, the active power of the DFIG, DC bus voltage of the DFIG and the voltage of PCC point are compared in the two different algorithms, which are the chaotic orthogonal particle swarm optimization and the ordinary PSO algorithm.

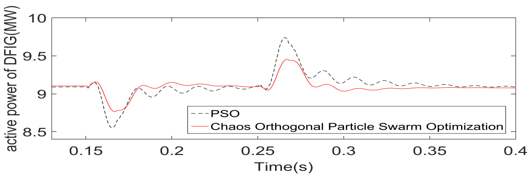

Figure 10. Active power with changing parameters comparison of the two methods.

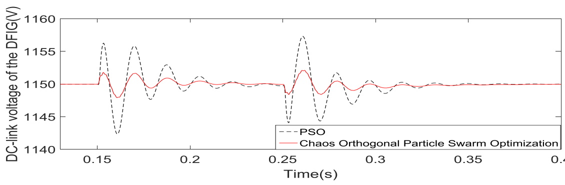

Figure 11. DC bus voltage with changing parameters comparison of the two methods.

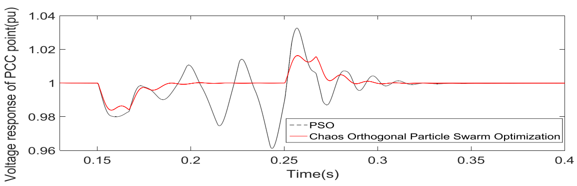

Figure 12. Voltage at the PCC with changing parameters comparison of the two methods.

The analysis of figure 10-12 shows that when the STATCOM condition changes, the optimization effect is not good when the controller parameters are optimized by the ordinary PSO algorithm, the voltage fluctuation of the PCC point is larger, the overshoot of the wind farm output is bigger and the response time is long. The specific performance is that the PCC point voltage fluctuates, the overshoot of the wind farm output increases and the response time is long. While using chaotic orthogonal particle swarm algorithm can reduce the overshoot of PCC point voltage, shorten the adjustment time, weaken the fluctuation of active power and DC bus voltage of DFIG, improve the anti-jamming performance of the system, and maintain the good dynamic performance of the wind farm.

5. Conclusion

In order to solve the multiple PI controller parameters simultaneous optimization problem of STATCOM and DFIG in wind farms, a method named chaotic orthogonal particle swarm optimization is proposed. This algorithm has a good optimization effect under two different operating conditions.

After optimization, in the event of voltage fluctuations, the controller's response speed and overshoot are significantly better than those optimized using normal PSO algorithms. It not only has a better compensation effect on the PCC point voltage, but also effectively improves the external characteristics of the DFIG-based wind power generation system.

Acknowledgments
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