PI Parameters Tuning for Sub-Synchronous Interactions in DFIG Based on GSSA Algorithm

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Abstract. The interaction between the control of power electronic devices and the series compensating capacitors is called sub-synchronous control interaction (SSCI). Because SSCI seriously affects the stability of the power grid, it has attracted much attention. In this paper, the initial population of salp swarm algorithm (SSA) is optimized based on good point theory and an improved SSA algorithm (GSSA) is proposed. Then, based on the improved GSSA algorithm, the PI parameters are adjusted to minimize the oscillation. Finally, the validity of the method is verified by simulation analysis. In addition, the robustness of the optimized parameters under different wind speeds and series compensation levels is studied. The results show that the optimized parameters can not only effectively suppress SSCI, but also have strong robustness in different working conditions.

Keywords: doubly fed induction generator (DFIG), PI parameter optimization, sub-synchronous control interaction (SSCI), improved Salp Swarm Algorithm

1. Introduction
With the rapid development of new energy, the problem of broadband harmonic oscillation caused by the access of a large number of power electronic equipment to the grid has become the focus of research. As a representative of new energy, wind power is widely used to improve the long-distance power transmission capacity through series complement transmission lines, which is an effective measure to absorb wind power [1]. However, the Interaction between the DFIG converter control and the compensation capacitance is easily to trigger the SSCI [2]. Since SSCI does not have the participation of the mechanical shafting system, the damping effect of the system on the oscillation is small, the oscillation divergence speed is faster, and the harm is greater. The sub-synchronous oscillation in the wind field in Texas [3] of the United States is typical SSCI types. With the gradual electronization of power system, the new type of subsynchronous oscillation (SSCI) caused by the dynamic interaction between converters and the power grid has become a research hotspot.

At present, the SSCI suppression methods for doubly-fed fans can be divided into two categories: one is to add FACTS devices, such as controllable series complement (TCSC) [4]. The significant disadvantage of adding FACTS devices is the high equipment and maintenance cost. Another type is the configuration of supplementary damping controller (SDC) [5-6], or the optimization of control parameters to increase the system software damping. The SDC methods in the Grid Side Converter (GSC) control of the DFIG are studied [7-8], while the corresponding SDC methods in the Rotor Side
Converter (RSC) control of DFIG are studied [9]. However, the changes of grid topology or operating conditions will bring many challenges to the parameter design of damping controller. Many studies have shown that SSCI is mainly related to the parameters of DFIG controller, especially rotor side control (RSC) parameters [10]. Therefore, engineers tend to adjust PI with optimization algorithm [11-12] to improved system performance. The eigenvalue analysis method and NSGA-III algorithm were used to optimize the converter parameters and effectively suppress the system oscillation [12]. However, it is difficult to establish the parametric model of the dynamic components accurately, which brings great challenges to the research.

In this paper, the problem of suppressing DFIG SSCI was transformed into the problem of PI parameter tuning. The calculation results of Simulink time domain simulation program were taken as the objective function, and the optimal parameter combination was found intelligently based on the improved Salp Swarm Algorithm (GSSA) to achieve the purpose of suppressing SSCI. The rest of the paper is as follows. The DFIG system is described in Section II. The improved SSA algorithm is constructed in section III. Section IV sheds light on the optimization results of DFIG PI parameters. Conclusions are drawn in Section V.

2. DFIG model
The scale of the wind farm studied is 100MW (66 * 1.5MV), which is represented by a single machine equivalent model. The whole wind power generation system is composed of wind wheel, gearbox, induction generator, RSC and GSC controllers, and transmission line. Its structure is shown in Figure 1. \( T \) in the figure is step-up transformer, \( R_L, X_L \) is the resistance and inductance, \( X_C \) is series compensation capacitor.

![Figure 1. DFIG wind generator model](image)

2.1. Model of RSC
As shown in Fig. 2. The RSC converter of DFIG system adopts d-q decoupling control strategy. The outer loop tracks the speed of the wind turbine, realizes the maximum power tracking, and then controls the output of active power. The inner loop adjusts \( i_{dr} \) and \( i_{qr} \) respectively to control the reactive power.

![Figure 2. Control block diagram of the RSC](image)

2.2. Model of GSC
As shown in Fig. 3. The GSC converter of DFIG system also adopts decoupling control. \( i_{dg} \) and \( i_{qg} \) control DC voltage and reactive power.
Based on eigenvalue analysis, the authors of [12] concluded that the oscillation mode of DFIG SSCI is highly sensitive to $V_{dc}$ and $\omega_r$. In order to reduce parameter dimensions, d and q axis control parameters were combined into a group. Finally, 4 groups of PI parameters to be optimized were determined.

### 3.1. Salp Swarm Algorithm

The SSA algorithm is derived from the research on the predation behavior of salps. In the predation process, the salps chain is guided by the leader at the front end, and the followers at the back end follow the previous individuals and collectively move towards the food.

Salp leader’s position update formula is as follows:

$$
\begin{align*}
    x_j^f &= \begin{cases} 
        F_j + c_1 \left( (u b_j - l b_j) c_2 + l b_j \right) & c_3 \geq 0 \\
        F_j - c_1 \left( (u b_j - l b_j) c_2 + l b_j \right) & c_3 < 0 
    \end{cases} 
\end{align*}
$$

where, $x_j^f$ and $F_j$ shows the position of the leader and food source in the $j$th dimension. $u b_j$ and $l b_j$ are upper and lower boundaries. $c_2$ and $c_3$ are random number in [0,1]. The coefficient $c_1$ adaptively adjust as the number of iterations changes, defined as follow:

$$
c_1 = 2e^{-\left(\frac{t}{t_{\text{max}}}\right)^2} \tag{2}
$$

The rules for the followers to update their positions are as follow:

$$
x_j^f = \frac{1}{2} a t^2 + v_0 t \tag{3}
$$

where, $t$ represents iteration, with a step of 1, and $a = \frac{v_{\text{final}}}{v_0}$ where $v = \frac{x-x_0}{t}$. Equation (3) can be deduced as follows:

$$
x_j^f = \frac{1}{2}(x_j^i + x_j^{i-1}) \tag{4}
$$

The GSSA algorithm flow chart is shown in Fig. 4.
3.2. Population initialization

Like other swarm intelligence algorithms, the population initialization of SSA algorithm also follows the principle of randomness. Its disadvantage is that the randomly generated population is not evenly distributed in the search space, which leads to the omission of better solutions. The good point set theory [13] is used to construct the initial population, so that the initial population is distributed evenly in the feasible region, and the population diversity is well maintained, which can avoid the algorithm falling into local optimum and improve the optimization performance. Authors in [14] used the theory of good point set to improve WOA algorithm and improve performance. Fig. 4 shows the comparison between the initial population generated randomly in the range of 0~10 and the initial population generated by using the theory of the good point set.

It can be seen from Fig. 5 that the randomly generated initial population may have some missing areas in the solution space, and the initial population generated by the good point set theory well solves this problem.

![Figure 4. flow of the SSA algorithm](image)

![Figure 5. Initial population distribution](image)

3.3. Fitness Function

The integral of the absolute value of the deviation between the instantaneous value of the electromagnetic torque $T_{em}(t)$ and the steady-state value $T_{em0}$ in $[t_1, t_2]$ is used as the objective function of the GSSA algorithm, as shown in Equation (5).

$$F(U) = \int_{t_1}^{t_2} |T_{em}(t) - T_{em0}| dt$$

subject to:

$$lb_{kp} \leq k_p \leq ub_{kp}$$

$$lb_{ki} \leq k_i \leq ub_{ki}$$

(5)
where, $lb$ is the lower bound on the range of values of $k_p$ and $k_i$, and $ub$ is the upper bound.

4. Simulation results and analysis

The doubly-fed wind power system model as shown in Fig. 2 is established by MATLAB/Simulink to verify the effectiveness of the nonlinear optimization method combining SSA algorithm and Simulink time-domain simulation program. SSCI may be triggered when the wind speed is too low or the fixed series complement of the system is high, or when the topology of the system is changed due to line faults, resulting in a sudden increase in the series complement.

4.1. Results of optimization model

As can be seen from Fig. 6a and 6b, in the system without optimized PI control parameters, the line fixed series compensation increases from 15% of 0-6s to 36% of 6-8s, and the active power $P$ of the Doubly-fed wind turbine occurs SSCI phenomenon. After 8 seconds, the series complement is increased to 40%, and the oscillation is in a divergent state. However, the PI parameter optimized by GSSA can effectively increase the system damping and suppress SSCI.

Fig. 6c shows the FFT analysis results of the phase A current. Before optimization, the SSCI oscillation frequency at 26.4 Hz. However, this frequency resonance is weakened under GSSA-PI control, and the current amplitude is reduced to the normal level.

From the preceding analysis, the converter parameter combination optimized by GSSA algorithm can effectively suppress the SSCI of the doubly fed fan. The optimization results of converter control parameters are shown in Table I.
Figure 6. GSSA algorithm optimization results (wind speed 10m/s)

Table 1. Optimization results of PI control parameters.

| Methods      | \( \omega_r \) Kp | \( \omega_r \) Ki | \( i_{dr} \) Kp | \( i_{dr} \) Ki | \( V_{DC} \) Kp | \( V_{DC} \) Ki | \( i_{dg} \) Kp | \( i_{dg} \) Ki |
|--------------|-------------------|-------------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| PI           | 3                 | 0.6               | 0.12            | 1.2             | 8              | 400            | 0.83           | 5              |
| GSSA-PI      | 3.36              | 0.84              | 0.0186          | 0.001           | 6.663          | 390.37         | 2.712          | 4.956          |

4.2. Robustness under different working conditions

In addition to the SSCI caused by the increase of series compensation, the low wind speed is also a reason. At the 6th second, the series compensation degree increased to 36% and remained unchanged. At the 7th second, the wind speed decreased from 10m/s to 6m/s. As can be seen from Fig. 7, after the 7th second, due to the wind speed drop, the active power showed a downward trend. SSCI showed a divergent state, while the control parameters optimized by GSSA could still effectively damp the oscillation.

Figure 7. Active power at different wind speed

The robustness of the proposed method to suppress SSCI at different series compensation levels is also considered. As can be seen from Fig. 8, at the 7th second, the series compensation level suddenly increases from 36% to 75%, and the PI control parameters optimized by the GSSA algorithm can still rapidly suppress SSCI and have better performance than GWO and SSA. The iteration curves of each algorithm are shown in Fig. 9.
5. Conclusion

In this paper, the subsynchronous interaction (SSCI) suppression problem of double-fed fans is transformed into the control parameter tuning problem. The initial population of the SSA algorithm is improved based on the theory of good point set, and the improved GSSA algorithm is combined with the Simulink simulation program to optimize the control parameters of the DFIG converter. Simulation results demonstrate that the optimized control parameters can suppress the SSCI of DFIG quickly and effectively. This suppression method is robust to changeable wind speed and series compensation levels.

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