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SSO analysis and SSDC parameter optimisation based on the wind farm connected to HVDC transmission system

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Abstract: The interaction between renewable energy generation and high-voltage direct current (HVDC) transmission system becomes an essential cause of the subsynchronous oscillation (SSO) problem. In this study, the permanent magnet synchronous generator-based wind farm connected to HVDC transmission system is studied. The susceptivity analysis is carried out to find the main influence factors of the SSO problem. Besides, a parameter design method for subsynchronous damping controller is proposed. The configuration and the performance indicator are discussed, and then the optimisation algorithm is developed based on hybrid genetic algorithm and electromagnetic transient simulation. Finally, the proposed design method is validated by simulation in PSCAD/EMTDC.

1 Introduction

In recent years, with the increasing penetration of renewable energy represented by wind power, the permanent magnet synchronous generator (PMSG)-type wind turbine (WT) has been applied widely in advanced large-scale wind farms [1]. Besides, due to the reverse distribution of energy source and load centre in China, wind power transmitted by high-voltage direct current (HVDC) system has become more and more common. The subsynchronous oscillation (SSO) problem has been recorded in the system with large-scale wind farms, which brings new challenges to the power grid. With the increasing scale of the wind farm as well as the widespread use of non-linear components such as power electronic devices in power system, the SSO problem is difficult to analyse and solve.

In the SSO events related to the wind farm, the SSO has the characteristics of multi-source and multi-form [2]. The literature studies the SSO mechanism of the interaction between the wind farm and the grid. Liu *et al*. [3] studied the possible causes of SSO of PMSG based wind farm by time domain simulation and eigenvalue analysis, and it is concluded that the reactance of the transmission line, the number of wind turbines, and the control of converters of the wind farm could all have an influence on the SSO. Gao *et al*. [4] considered that the measurement delay of feedforward DC-capacitor voltage is the main cause of SSO for PMSG based wind farm connected to the grid.

The suppression method of SSO could be divided by the implementation position, which is either on the source side or on the grid side. The structure parameters of the source side/grid side could be optimised, and additional SSO suppression devices could be installed.

For the grid side, the suppression methods of SSO mainly depend on the installation of additional devices on the transmission lines where SSO is likely to happen. Normally, the AC transmission line with series compensators or DC transmission line of HVDC system is considered. On the one hand, SSO could be eliminated by breaking the condition of oscillation, such as the installation of blocking filter. On the other hand, the risk of SSO could be suppressed by the positive electrical damping of the power device itself or by the additional positive electrical damping, such as serial and parallel FACTS devices [5, 6] and the installation of subsynchronous damping controller (SSDC) in HVDC system [7].

For the source side, the commonly used suppression methods of SSO mainly include the optimisation of the converter control parameters of the wind farm and the implementation of additional devices on the machine side. [8] proposed a parameter optimisation method of the converter control of the wind farm. Liu *et al*. [3] presented a possible solution which applies the SSDC on the grid-side converter of the wind farm. [9] applied FACTS devices on the machine side to realise the suppression of SSO in the target wind farm system.

As an additional device, SSDC is relatively economical and easy to realise, which is suitable for the SSO suppression in PMSG based wind farm connected to HVDC transmission system. However, few studies concentrate on the time-domain performance indicator of SSDC to optimise its parameters.

In this paper, the small-signal model of the PMSG-based wind farm connected to HVDC transmission is established, through which the participation factor analysis is carried out. The state variables that have an influence on the SSO of the studied system are determined, from which the optimal installation position of SSDC is proposed. Then, taking the stability of the system into consideration, the time-domain performance indicator of SSDC is put forward. In order to design the parameters of SSDC, the optimisation is carried out on PSCAD/EMTDC platform, based on the performance indicator and hybrid genetic algorithm (HGA).

2 SSO susceptivity analysis

2.1 Studied system

In the studied system shown in Fig. 1, a PMSG-based wind farm is applied as the source, and the power is transmitted by HVDC system. Meanwhile, the turbogenerator and the wind farm are connected to PCC after step-up transformers.

In general, under the condition that the type and operation conditions of the wind turbines in one farm are basically the same, the PMSG-based wind farm could be represented by a single equivalent wind turbine. The parameters of the system are listed in Table 1.

The small-signal model of the system is developed by the linearisation of state equations near the steady state. Neglecting the state of the turbogenerator, the system consists of 21 state variables related to the wind farm and HVDC system, as given by (see (1)) where θ_1 and θ_2 are the torque angles of the blade and the generator, respectively, ω_1 and ω_2 are the corresponding angular speed, ψ_{ds} and ψ_{qs} are the d and q component of the flux linkage, respectively, x_1, x_2, x_3 and x_4 are the control factors of the grid-side converter,

V_{DC} is the DC current of the converter, x_5, x_6 and x_7 are the control factors of the machine-side converter, i_{Lx}, i_{Ly}, u_{cx} and u_{cy} are the x/y component of the current of line impedance and the voltage of the series compensated capacitor, respectively, I_{dR} and I_{dI} are the DC current at the rectifier and inverter side in HVDC system, and V_{dM} is the DC voltage of HVDC system.

2.2 Susceptivity analysis

Based on the small signal and considering that the capacity of the wind farm is 500MW, the eigenvalue analysis is carried out in MATLAB. The eigenvalues whose corresponding oscillation mode is in subsynchronous frequency range are listed in Table 2.

According to Table 2, there are three SSO modes in total, among which one unstable SSO mode exists. In this case, the unstable mode is considered to be the dominant mode whose frequency is 9.44 Hz. To analyse the state variables that affect this oscillation mode, the participation factors are studied, and the result is shown in Table 3.

As demonstrated in Table 3, the control of grid-side converter is the most important factor of the dominant SSO mode, and the DC voltage of the converter is another important element. Besides, the current of the transmission line also affects the SSO.

3 SSDC optimisation design

As a kind of additional control, SSDC suppresses the SSO by providing a positive electrical damping for the system in the subsynchronous frequency range. Based on the SSO analysis in the previous section, a SSDC design method is proposed to eliminate the risk of SSO.

3.1 SSDC structure

Based on the above analysis, the relationship between the SSO and the control of the grid-side converter is obvious. Therefore, in order to combine the control effect and the response speed, the SSDC is attached to the inner loop of the DC voltage control on the grid-side converter, and the structure is shown in Fig. 2.

The block of SSDC is also shown in Fig. 2. It consists of a band-pass filter, a compensator, and a limiter. ΔV_{dc} is applied as the input signal. Also after the extraction of subsynchronous frequency through the band-pass filter, the phase correction to provide positive electrical damping is achieved by the compensator link. Then after the amplitude limiter to control the maximum output, the signal is finally attached to the inner-loop of DC voltage control on the grid-side converter.

The compensator link is composed of a phase correction link and a constant gain. The phase correction link applies lead–lag correction, which could avoid the disturbance of the system exceeding subsynchronous frequency range by SSDC. Its format could be expressed as

$$C(s) = G\left(\frac{\alpha T s_1 + 1}{T_1 s + 1} \cdot \frac{\beta T_2 s + 1}{T_2 s + 1}\right)^m \tag{2}$$

where $\alpha > 1$, and $(\alpha T_1 s + 1)/(T_1 s + 1)$ corresponds to lead; $\beta = (1/\alpha) < 1$, and $(\beta T_2 s + 1)/(T_2 s + 1)$ corresponds to lag; T_1 and T_2 are, respectively, the time constant of the lead and the lag link. The value of m is decided by the need of the phase compensation. In general, $m = 1, 2$ could satisfy the requirement.

The fourth-order Butterworth band-pass filter is used. Besides, as the SSDC is attached to the inner loop of the grid-side converter, the amplitude should not exceed the rating of the inner current control by 0.1 pu.

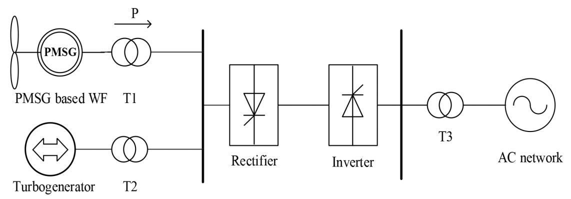

Fig. 1 *System schematic diagram*

Table 1 Parameters of the system

Parameter	Value
capacity of WT	5 MW
rated terminal voltage of WT	0.69 kV
capacity of HVDC	1000 MW
rated DC voltage of HVDC	500 kV
capacity of turbogenerator	600 MW

Table 2 Eigenvalues in subsynchronous frequency range

Sequence	Eigenvalue	Frequency, Hz
$\lambda_{1,2}$	**2.84 ± 59.32i**	**9.44**
$\lambda_{3,4}$	−1.68 ± 3.32i	0.53
$\lambda_{5,6}$	−26.18 ± 107.39i	17.09

The bold value indicates the pair of values corresponding to the module.

Table 3 Participation factors of the dominant mode

State variable	Participation factor
Δx_2	0.46
ΔV_{DC}	0.41
ΔI_{LX}	0.12
Δx_1	0.01

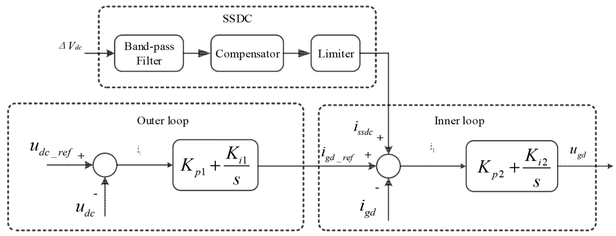

Fig. 2 *Diagram of the grid-side converter with SSDC*

3.2 Parameter design

The compensator link is the key part of SSDC, whose parameters would have much impact on the performance of SSDC. Thus, the parameter values of the compensator need to be well designed. In order to quantify the performance of SSDC, a time-domain performance indicator is put forward. Also on this basis, the optimisation is carried out to get reasonable parameter values for the compensator.

3.2.1 Performance indicator: While the SSDC is implemented in the system, the system response could be divided into the transient response and the steady-state response. SSDC should meet the demand in these two stages.

On the one hand, it should be ensured that the transient oscillation quickly attenuates in a relatively brief period. On the other hand, the oscillation amplitude should be kept small after the system enters steady state.

$$\Delta X = \begin{array}{l} [\Delta\theta_1, \Delta\theta_2, \Delta\omega_1, \Delta\omega_2, \Delta\psi_{ds}, \Delta\psi_{qs}, \Delta x_1, \Delta x_2, \Delta x_3, \Delta x_4, \\ \Delta V_{DC}, \Delta x_5, \Delta x_6, \Delta x_7, \Delta i_{Lx}, \Delta i_{Ly}, \Delta u_{cx}, \Delta u_{cy}, \Delta I_{dR}, \Delta I_{dI}, \Delta V_{dM}]^{\mathrm{T}} \end{array} \tag{1}$$

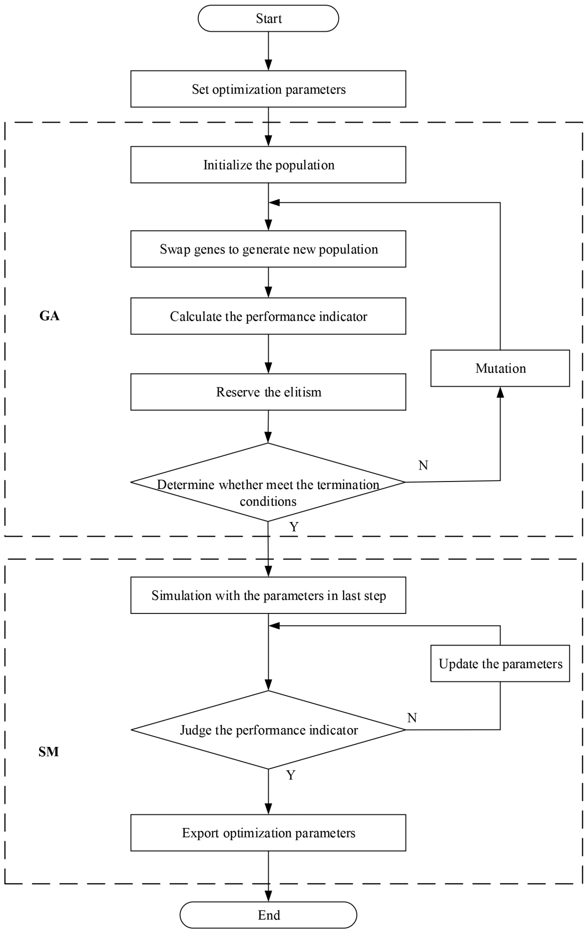

Fig. 3 *Flow chart of the optimisation of the compensator*

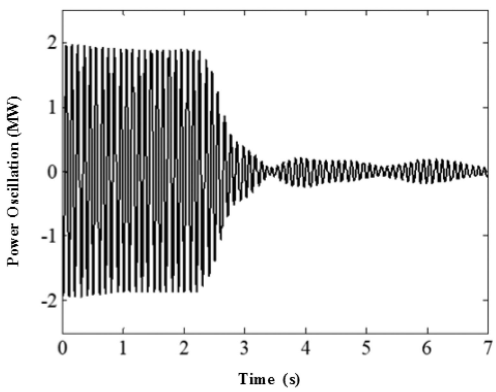

Fig. 4 *Simulation result of power with SSDC applying GA*

Table 4 Parameters of compensator with GA

Parameter	Value
G	2.99
T_1	0.77
T_2	2.91
α	2.92

As the SSO of PMSG-based wind farm associates with the oscillation of the wind power P_g, it is possible to take the deviation of P_g as the variable of the performance indicator ΔP_g. The performance indicator is in the form of integral of square error, including the transient response and the steady-state response. Firstly, assuming that the SSDC is applied at t_0 and that the system should return to the steady state before t_1. ΔP_g in this period corresponds to the transient response. Then, calculating ΔP_g in the steady state between t_1 and t_2 as the steady-state response. Thus, the performance indicator between t_0 and t_2 is given as

$$\Delta P_g = \rho \int_{t_0}^{t_1} \left(P_g(t) - P_{\text{set}}\right)^2 \mathrm{d}t + (1-\rho) \int_{t_1}^{t_2} \left(P_g(t) - P_{\text{set}}\right)^2 \mathrm{d}t \quad (3)$$

where $P_g(t)$ is the measured value of the power of the wind farm, and P_{set} is its rated value, ρ is the weight of the transient response.

3.2.2 Optimisation algorithm: For the non-linearisation of the studied system, the electromagnetic transient model can more precisely reflect the characteristics of the power electronic components than the small-signal model. Therefore, the electromagnetic transient model is applied for the optimisation.

Based on the model and the performance indicator, the hybrid genetic algorithm (HGA) is applied for the optimisation of compensator link. The optimisation is firstly carried out based on genetic algorithm (GA) for its global convergence rate is relatively fast. Then, simplex method (SM) is applied on the basis of the result of GA, because of the quick local convergence rate. The detailed optimisation process is shown in Fig. 3. The detailed steps are listed as follows:

1. *Optimisation parameter setting*: Determine the initial values of GA, including the initial population N, the maximum generation K_G, the elite population N_{elit}, the population of the mating pool N_{ec}, the mutation rate p_m and the maximum difference between two successive populations ξ. For SM, the allowable deviation of the performance indicator is ε.
2. *GA optimisation*: The optimisation is performed and the performance indicator is calculated in each iteration.
3. *Termination of GA*: The algorithm will end while one of the following two conditions are met:

   a. The difference of the performance indicator between two successive generations is $<\xi$.
   b. The maximum generation K_G is reached.

4. *SM optimisation*: The optimal solution obtained by GA is applied to SM as the initial values.
5. *Termination of SM*: The optimisation will terminate while the deviation of the performance indicator is $<\varepsilon$.

4 Simulation

To validate the proposed SSDC design method, the detailed electromagnetic transient model in Fig. 1 is built in power systems computer aided design (PSCAD)/electronmagnetic transients including DC (EMTDC) platform. The rated power of the wind farm $P_{\text{set}} = 500$ MW. The amplitude limit is set to ±0.1 pu.

The compensator takes the form of a single lead–lag link. Also the weight of transient response of performance indicator is $\rho = 0.6$ The HGA is used to determine the parameters of the compensator. First, set the parameters of the algorithm. For GA, $N = 30$, $K_G = 100$, $N_{\text{elite}} = 8$, $N_{\text{ec}} = 20$, $p_m = 0.05$ and $\zeta = 0.05$. For SM, $\varepsilon = 3.0$.

The simulation result of the optimisation by GA is shown in Fig. 4. Initially, the amplitude of the power oscillation is up to 2 MW. Also at $t_0 = 2$ s, the SSDC is put in the system. Besides, $t_1 = 3$ s and $t_2 = 7$ s. According to Fig. 4, the SSO attenuates quickly once after t_0. The system is back to the steady state at 3.5 s, then the power oscillation maintains at 0.2 MW, but certain periodic oscillation remains.

The optimised compensator parameters are shown in Table 4.

The parameters in Table 4 are implemented in SM as the initial values. Other conditions of the system keep unchanged. The simulation result by SM is shown in Fig. 5. As could be seen from the simulation result, the system returns to the steady state at 3.3 s, and the power oscillation amplitude remains at around 0.18 MW. Compared with the initial solution in Fig. 4, the system restores

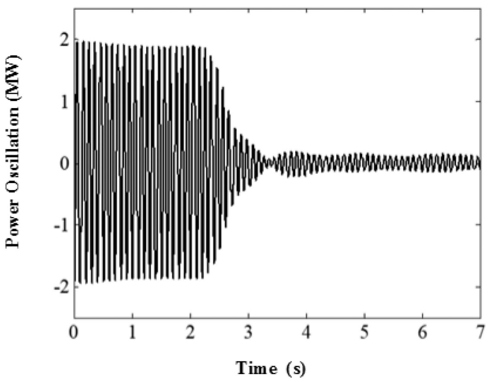

Fig. 5 *Simulation result of power with SSDC applying SM*

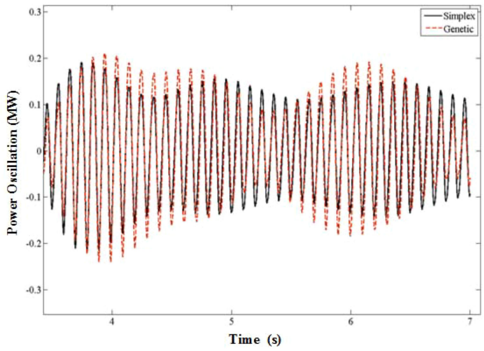

Fig. 6 *Simulation result comparison in steady state between GA and SM*

Table 5 Parameters of compensator with GA

Parameter	Value
G	2.99
T_1	0.77
T_2	2.91
α	2.92

steady in shorter time, and the periodic oscillation almost disappears.

Fig. 6 compares the simulation results of GA and SM in their steady state, the dotted line represents the first optimisation result, and the solid line corresponds to the last. The steady-state oscillation of the second optimisation is relatively smaller than the first one.

The final parameters of the compensator obtained from the simulation are shown in Table 5.

From the above simulation results, the SSO elimination of the designed SSDC is effective, and SSO attenuation speed is relatively fast. Therefore, the proposed SSDC design method is valid.

5 Conclusion

In this paper, the SSO analysis of the PMSG-based wind farm connected to HVDC links is firstly carried out based on the small-signal model and the SSDC design method is proposed. The SSO analysis results show that the control of wind turbine converter and the reactance of the transmission line are dominant factors of the SSO mode. According to the analysis results, the SSDC design method is presented. The structure of SSDC is determined, and the performance indicator of SSDC is proposed. HGA is applied to optimise the SSDC parameters. The simulation results show that the proposed method can effectively suppress the risk of SSO and has certain practical value.

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