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The research of SSR which can be restrained by photovoltaic grid connected

Kuan Li¹,³, Meng Liu¹, Wei Zheng², Yudun Li¹ and Xin Wang¹

¹ State Grid Shandong Electric Power Research Institute, Jinan, 250002, China;
² Shandong Zhongshi Yitong Group Co.,Ltd., Jinan, 250002, China
³ lk_0313@sina.com

Abstract. Utilization of photovoltaic power generation has attracted considerable attention, and it is growing rapidly due to its environmental benefits. The series capacitive compensation is needed to be introduced into the lines which could improve the transmission capacity. However, the series capacitive compensation may lead to sub-synchronous resonance (SSR). This paper proposes a method to restrain the SSR based on photovoltaic grid connected which is caused by series capacitive compensation. Sub-synchronous oscillation damping controller (SSDC) is designed based on complex torque coefficient approach, and the SSDC is added to the PV power station’s main controller to damp SSR. IEEE Second benchmark model is used as simulation model based on PSCAD/EMTDC. The results show that the designed SSDC could restrain SSR and improve stability in PV grid connected effectively.

1. Introduction

Solar energy has attracted widespread attention gradually due to series of benefits such as wide distribution, renewable and free of air pollution, etc. Photovoltaic power generation can be an environment-friendly and an effective way to ease the fossil energy consumption. In order to improve the efficiency of photovoltaic power generation, plenty of researches have been done such as the maximum power point tracking (MPPT) at solar photovoltaic array [1-3]. Designing of large-scale photovoltaic grid and analyzing the grid impact have become focus of current research to improve the efficiency and stability of photovoltaic grid. The most widely used way of network control is double closed-loop decoupling control strategy currently [4-5]. Studies have been done on deadbeat control, fuzzy control, proportional control and robust control resonance to replace the original PI control to improve the stability of PV grid [6].

Series capacitive compensation is an effective way to increase transmission capacity and improve transient stability in AC transmission system. However, one of the hindering factors for the extensive use of series capacitive compensation is the potential risk of sub-synchronous resonance (SSR), which is the electrical energy amplified phenomenon between the power grid and the turbine-generator shaft systems. Sub-synchronous resonance is the torsional vibration of shaft system between generator shaft modules, which will cause damage in shafting system and even affect the overall security and stability of the power system.

A lot of researches have been done in identification methods and restraining methods about sub-synchronous resonance. Identification methods include Prony, Matrix Pencil (MP) and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT). Methods to restrain SSR varied,
where Static Var Compensator (STATCOM) and Supplementary Excitation Damping Controller (SEDC) had been studied much.

References [7] proposed that restrain the SSR caused by series capacitive compensation through double-fed wind turbine connected to grid. The designed supplementary controller was added to the wind farm main controller. The IEEE second benchmark model was used as the simulation model to verify the effective of supplementary controller. And a control method was proposed to restrain the synchronous oscillation (SSO) caused by wind turbines in the process of wind farm connected to grid in this paper [8-10].

Virtually, there is no research reported on adding Sub-synchronous Oscillation Damping Controller (SSDC) on the main controller of PV grid to restrain SSR. This paper investigated the potential use of supplemental control of SSDC based on PV grid for damping SSR. Photovoltaic field of 200×1MW was connected to the grid in the simulation model. The IEEE second benchmark model was used as the simulation model of SSR which was building by PSCAD/EMTDC. Simulation results show that the additional controller could restrain the SSR which caused by AC series capacitive compensation rapidly and effectively.

2. Method
The topology of photovoltaic grid is shown in Figure 1. It can be seen that the IEEE Second Benchmark Model generator shaft consists of a high-pressure cylinder, a low pressure cylinders, a generator and an exciter in Figure 1. The photovoltaic grid is incorporated into the AC grid via a DC/AC inverter and a transformer $T_r$.

![Figure 1. Photovoltaic grid connected topology.](image)

The purpose of this paper is damping SSR which is caused by series capacitive compensation based on photovoltaic grid connected to grid. And the maximum power point tracking is not discussed here because of it is not the key point in this paper.

2.1. PV grid control principle
The topology of the three-phase two-level voltage sourced converter, which was used as an inverter in the Photovoltaic grid, was shown in Figure 2.

![Figure 2. Voltage sourced converter topology.](image)
Pulse width modulation (PWM) technology and double-loop control strategy were adopted to modulate VSC, where the three-phase voltage and current were converted into D-Q variables based on synchronous rotating coordinate system by Park transform.

The three-phase dynamic equations at the AC side of the D-Q coordinate system by Park transform can be represented mathematically as follows:

\[
\begin{align*}
    \frac{du_d}{dt} &= u_d + \omega L_i_d - (R_i_d + L \frac{di_d}{dt}) \\
    \frac{du_q}{dt} &= u_q - \omega L_i_q - (R_i_q + L \frac{di_q}{dt})
\end{align*}
\]  

(1)

Where the subscript \(d\) and \(q\) are stand for electric component of D-axis and Q-axis.

In order to restrain the SSR effectively, Constant DC voltage was used as active component of the control volume and Constant AC voltage was used as the reactive component of the control volume. The Control logic diagram was shown in Figure 3.

\[\text{Figure 3. Decoupling control logic diagram.}\]

Where the control volume \(m\) and \(\delta\) of the VSC are represented as follows:

\[
m = \frac{2(u_d^2 + u_q^2)}{U_{dc}}
\]  

(2)

\[
\delta = \arctan \frac{u_d}{u_q}
\]  

(3)

The letters with subscript star represent the reference value of the control quantities and the letters with no subscript indicate the measured value of the control quantities in Figure 3. According to the SSR principle, when the resonant frequency plus the unit shaft torsional vibration frequency equal 50Hz, coupling between the generator and the grid may be excited to be enlarged. The output signal of the SSDC was added to the reactive power controller of inverter, then the compensation current produced the electromagnetic torque component, which has the same frequency of the oscillation mode. Thus, the purpose of restrain generator shafting oscillates was achieved. The supplementary control signal of subsynchronous damping controller is shown in Figure 4.

\[\text{Figure 4. Introducing an SSR supplementary control signal at the reactive power control loop.}\]

2.2. Complex torque coefficient method

Electromagnetic torque increment of the generator can be expressed as follows:

\[
\Delta T_e = K_e \Delta \delta + D_e \Delta \omega
\]  

(4)
Where $\Delta T_e$ is stand for electromagnetic torque increment of the generator, $\Delta \delta$ and $\Delta \omega$ are stand for power-angle increment in rad and rotate speed increment of the generator, $K_s$ and $D_e$ are synchronizing torque coefficient and damping torque coefficient. The units of $\Delta T_e$, $K_s$ and $D_e$ are all per unit. When Laplace transform is done to formula (4), the expression for coefficient of electric damping is as follows:

$$D_e(f) = \text{Re}\left( \frac{\Delta T_e(f)}{\Delta \omega(f)} \right)$$  \hspace{1cm} (5)

In order to damp the SSR, the phase deviation between the generator speed deviation and the electromagnetic torque deviation must be within the range from 0° to 90° to meet the demand of $D_e(f) > 0$.

2.3. Design of subsynchronous damping controller

Phase deviation between the generator speed and torque should be measured, and then phase compensation is presented to achieve the purpose of sub-synchronous damping control restrain SSR effectively. The block diagram of SSDC is shown in Figure 5.

![Figure 5](image)

**Figure 5.** The block diagram of SSDC.

(1) Design of the filter

When a mode is damped, the others modes should not be affected in the SSDC design. A filter could isolate the adjacent modes effectively. The filter consists of a second-order band-pass filter and a second-order band-stop filter with cascaded structure is proposed. The bandwidth of the filter is set as 3Hz. The transfer function of the filter is presented as follows:

$$G_i(s) = \frac{\omega_s}{s^2 + 6\pi s + \omega_s^2} \cdot \frac{s^2 + \omega_{s1}^2}{s^2 + 6\pi s + \omega_{s1}^2}$$ \hspace{1cm} (6)

(2) Phase compensation link

Different angular velocity increment $\Delta \omega$ in different oscillation modes and phase deviation oscillation modes of the electromagnetic torque are get. If the required compensation angle is positive, phase compensation can be achieved using lead-lag. The transfer function of the phase compensation can be represented as follows:

$$F_i(s) = \frac{1 + sT_1}{1 + sT_2}$$ \hspace{1cm} (7)

$T_1$ and $T_2$ can be obtained by the following formula (8).

$$\begin{align*}
a &= \frac{(1 - \sin \theta)}{(1 + \sin \theta)} \\
T_1 &= a / \left( \omega_i \cdot \sqrt{a} \right) \\
T_2 &= a \cdot T_1
\end{align*}$$  \hspace{1cm} (8)

Where $\theta$ is stand for phase to be compensated, $n$ is the number of cascaded phase compensation links. In order to get perfect effect of phase compensation, you can select multiple forms of the cascade phase compensation links.

If the required compensation angle is negative, the transfer function of the phase compensation can be represented as follow:
During the phase compensation you should note the role of the phase shift.

(3) Gain links
When the phase compensation angle is positive, the amplitude after the phase compensation varies, the gain $K_i$ of each control mode need to be adjusted in order to ensure the amplitude of signal amount each mode changes little after phase compensation.

When the phase compensation angle is negative, the amplitude of the signal will not be affected according to formula (9), so the gain move to this link will be a constant 1.

3. Simulation analysis
Simulation was done in PSCAD/EMTDC simulation software with the grid of IEEE Second Benchmark Model and photovoltaic grid. The topology of the system is shown in Figure 1.

3.1. Without SSDC
(1) Time-domain simulation
Applying a three-phase grounding fault in the grid side when $t=2s$ and duration 0.02s. The simulation result of the generator cylinder speed deviation were shown in Figure 6 which without SSDC.

![Figure 6. The speed deviation of shafting without SSDC.](image)

It can be seen from the Figure 6 that system disturbance causes diverging oscillation of the generator speed, which may conduce instability of the system. Active power and reactive power of the photovoltaic grid after a system disturbance were shown in Figure 7.

![Figure 7. The active power and reactive power of PV grid connected.](image)
It can be seen from Figure 7 that the photovoltaic grid are stable at first with 197MW active power and 465Mvar reactive power. When system disturbances occur, active power and reactive power exist with fluctuation divergent state and the system is unstable after 12.5s.

(2) Analysis of the characteristic roots

Characteristic roots of the generator speed’s signal were analyzed by matrix pencil algorithm proposed by M. L. Crow. Characteristic roots can be obtained in different oscillation frequencies. SSR mode analysis after the photovoltaic grid connected to power grid are shown in Table 1.

| Mode   | Oscillation Frequency (Hz) | Attenuation factor | Damping ratio (%) |
|--------|---------------------------|--------------------|-------------------|
| Mode 1 | 24.5846                   | -0.0097            | 0.00628           |
| Mode 2 | 32.2135                   | -0.0057            | 0.00282           |
| Mode 3 | 51.9852                   | 0.0082             | -0.00251          |

It can be seen in Table 1 that there are three oscillation modes in the photovoltaic grid system. Each mode is close to zero damping. The weak damping mode is conducive to cause oscillation divergence, which is consistent with the time-domain simulation.

3.2. With SSDC

(1) Time-domain simulation

Before introduce SSDC into the system, the phase shifting angles and the offset angles $\Delta a_j$ should be knew. The SSDC control signal at the PV reactive power control loop is shown in Figure 4. The speed signals of the generator when SSDC added into the system are shown in Figure 8.

![Figure 8](image-url) The speed deviation of shafting with SSDC.

It can be seen from Figure 8 that if a system disturbance occurs, the generator speed oscillates severely. While add the SSDC into the system, the oscillation of generator speed will be stable rapidly. Figure 9 shows that the SSDC cause active and reactive power of the PV grid oscillating severely in a short time, while it makes the system stable and the oscillation will not diverge in the long run. Anyway, introduce the SSDC into the system ultimately benefit the stability of the system.
(2) Analysis of the characteristic roots with SSDC

Characteristic roots of the generator speed signal with SSDC were analyzed by matrix pencil algorithm proposed by M. L. Crow. The result is shown in Table 2.

| Mode | $f$ (Hz) | Attenuation factor | Damping ratio (%) |
|------|---------|--------------------|------------------|
| 1    | 24.5482 | -1.2549            | 0.81             |
| 2    | 32.3549 | -0.9584            | 0.47             |
| 3    | 51.6258 | -0.0104            | 0.0032           |

Comparing Table 1 and Table 2, the results show that all of the damping is positive and damping ratio in each mode of the system with SSDC has been improved greatly. The system restore to stable quickly, which is in consistent with the time-domain simulation result in Figure 9.

4. Conclusions

The SSDC was introduced to the main controller of the PV grid which is used to restrain the SSR caused by AC series capacitive compensation. The IEEE Second Benchmark Model is used as simulation model, and the simulation results show that the SSDC added to the main controller can restrain the SSR effectively.

Damping SSR and stabilizing the grid both can be realized through renewable energy integration. This method has comparatively strong practicality in engineering because the designed controller could be realized through generator speed signal only.

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