Impact of series compensation on operation performance of large-scale PV plants

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Abstract: Application of series compensation transmission lines to enhance the long-distance transmission capability of photovoltaic (PV) plants is the most economical technical measure. To investigate the impact of series compensation on operating performance of large-scale PV plants, the simulation research is performed in this study. The detailed model of large-scale PV plants connected to the grid through series compensated lines is developed using power systems computer aided design (PSCAD)/electromagnetic transients including DC (EMTDC) software. Using the detailed model, the performances of active and reactive power outputs, voltage and current profiles of PV plants are investigated for different levels of series compensation and strengths of AC system during short-circuit faults. The simulation results show that series compensation and strong AC system can effectively improve the transient operation performance of the PV power plant. With the increase of the series compensation degree and the strength of AC system, the fault ride-through performance of PV plants is improved.

1 Introduction

With the increasing of photovoltaic installed capacity in power systems, solar energy will play an important role in achieving the goal of non-fossil consumption accounting for 20% primary energy in 2030 according to the Chinese ‘13th Five-Year’ solar energy development planning. The large-scaled development and the centralised integration to power grids have become an important way of utilisation of solar energy resources in China. PV plants centrally developed are far away from load centre, and PV generation power needs to be transmitted to the load centre by long transmission lines.

Application of series compensation transmission lines to enhance the long-distance transmission capability of PV plants is the most economical technical measure. In China, some PV plants are planned to transmit the large-scale PV power using series compensated lines. However, the impact of series compensation on the operating performance of large-scale PV plants has not yet been investigated. Therefore, it has become an urgent need for the power industry to investigate the impact of series compensation on the operation performance of large-scaled PV plants.

The operation performance of large-scale renewable energy power plants such as wind farms or PV plants are mainly affected by the control strategy of the generation system; thus, may be different from that of traditional power plant. In addition much research on dynamic performance of wind farms has been done. Short-circuit ratio (SCR) is often used as an index of the system strength on which the performance of wind farms in a power system is highly dependent [1]. The literature [2] investigates the effect of the SCR on the performance of wind turbine models including transient stability, low-voltage ride-through (LVRT), and wind farm oscillations. The controls and characteristics of individual wind turbine generator of various designs and their modelling in stability studies are discussed in [3, 4]. Also, there have been many papers involving the performance of large-scale wind farms and their impact on the voltage and frequency of the system [5, 6].

As for PV generation, the literature [7] investigated the performance of large-scale PV system under various fault conditions. The short-circuit current performance was focused on in the literature [8]. Furthermore, the fault behaviour of PV power plant and its influence on relay protection of transmission line are studied in [9]. However, the previous work has not yet investigated the impact of series compensation on the operating performance of large-scale PV plants. Also, the previous work has hardly considered the operating performance of large-scale PV plants for different strengths of AC system. The related work has been done in this paper, and the impact of series compensation on large-scale PV plants is investigated.

In this paper, Section 2 develops a detailed model of large-scale PV plant connected to the utility grid with series compensated transmission lines on PSCAD/EMTDC platform. In Section 3, the simulation results of different levels of series compensation and strengths of AC system are presented and discussed. Finally, the conclusion is presented in Section 4.

2 PV generation system model

The PV generation system model established in this paper is adapted from the PV model in [10] and it mainly consists of PV array model, DC–DC converter (booster converter), PV inverter, pad-mounted transformer, collector circuits, step-up transformer, series compensated transmission lines, and utility grid equivalent model, as shown in Fig. 1.

2.1 PV array

2.1.1 Equivalent circuit: A solar cell can be modelled using an electrical equivalent circuit that contains a current source anti-parallel with a diode, a shunt resistance, and a series resistance [11], as shown in Fig. 2. The equation governing the internal currents can be expressed based on Kirchhoff current law as

\[ I = I_{ac} - I_d - I_{sh} \]  \hspace{1cm} (1)
where $I_{sc}$ is the irradiance current, which is generated when the cell is exposed to sunlight; $I_d$ is the current flowing through the anti-parallel diode, which induces the non-linear characteristics of the solar cell; $I_{sh}$ is the shunt current following through the shunt resistor $R_{sh}$.

Substituting the relevant expressions for the diode current $I_d$ and the shunt branch current $I_{sh}$:

$$I = I_{sc} - I_o \exp \left( \frac{q(V + IR_{sh})}{nkT} - 1 \right) - \frac{V + IR_{sh}}{R_{sh}}$$

(2)

where $q$ is the electronic charge ($q = 1.602 \times 10^{-19}$ C); $k$ is the Boltzmann constant ($k = 1.3806503 \times 10^{-23}$ J/K); $n$ is the ideal constant of the diode; $T$ is the temperature of the cell; $I_o$ is the diode saturation current; $R_{sh}$ and $R_{sr}$ are the series and shunt resistance, respectively.

2.1.2 Output and fault ride-through performance: Taking into account the characteristic of PV array, the $P-V$ curve and $I-V$ curve of the PV array used in this model are shown in Fig. 3. $P$ is the output power of PV array, $V$ is the PV array terminal voltage, and $I$ is the output current.

It is observed in Fig. 3 that, below the optimal voltage ($V_{opt}$), the power increases with the increase of terminal voltage, and PV behaviour is similar to a current source. Above the $V_{opt}$, PV output decreases with the increase of terminal voltage until it reaches zero at open-circuit voltage, and PV behaviour is similar to a voltage source.

When the PV system is running at the maximum power point and the grid voltage drops instantaneously, the DC bus voltage $U_{dc}$ will increase flashily in terms of the power balance principle. As the $P-V$ curve shows, the increase of the voltage leads to the decrease of the output power of the PV array until the new power balance point is reached. The DC bus will remain stable, and the $U_{dc}$ maximum will not exceed the open circuit voltage of the PV array. Therefore, it is inherently advantageous for the PV grid-connected system to achieve LVRT.

2.2 DC–DC converter

The DC–DC converter of PV generation is used to step down/up the PV terminal voltage (buck/boost converter). In this paper, a boost converter, consisting of a low pass filter, an inductor, an insulated gate bipolar transistor switch, a diode and a capacitor, is adopted as shown in Fig. 4.

The DC–DC converter can also achieve maximum power point tracking (MPPT) by adjusting PV array terminal voltage. The control scheme is shown in Fig. 5 and the incremental conductance algorithm is implemented in the MPPT model of PSCAD/EMTDC [12, 13].

2.3 PV inverter

The PV inverter is the point conversion from DC to AC system. In small distributed applications, the PV inverter is usually single-phase while three-phase PV inverter is usually designed with a large rating (1–2 MW and above) for industry application. In general, a PV inverter consists of a DC capacitor and three pairs of power semiconductors, as shown in Fig. 6. In most applications, the three-phase inverters are current-regulated voltage-source inverter. Voltage oriented control is utilised in this paper [14]. The control structure of PV inverter is shown in Fig. 7.
2.4 Aggregated PV model

The cables between the devices in the PV generation unit are very short, so their influence can be ignored compared with collector system [15, 16]. The detailed model of PV generation unit is scaled up to the aggregated model of the PV station in terms of their capacity. The current of the aggregated model can be expressed as

\[ I_{\text{aggr}} = n \times I_{\text{unit}} \]  

where \( n \) is the number of generation units, \( I_{\text{unit}} \) is the output current of the PV unit and \( I_{\text{aggr}} \) is the output current of aggregation model.

2.5 Effect of series compensation level and SCR

To study the operation performance of large-scale PV plants connected with the series compensated lines for different levels of series compensation and strengths of AC system, the definition of series compensation degree and SCR are illustrated in Fig. 8.

The series compensation level, \( K_C \), is defined by

\[ K_C = X_C/X_L \]  

where \( X_C \) is the capacitance of series compensation capacitor. Thus, the transmission power is shown as follows:

\[ P = U_1U_2 \sin \delta/(X_L - X_C) \]  

If \( \delta \) is equal in (6) and (7), the transmit power of the series compensation lines will be \( N \) times as large as the transmit power of the original lines

\[ N = X_L(X_L - X_C) = 1/(1 - K_C) \]  

3 Simulation and discussion

The detailed model of the PV system is built on the simulation platform, PSCAD/EMTDC, as shown in Fig. 9 [9]. The rated power of the PV unit is scaled up to 500 MW to represent the PV plant model. The PV units are connected to the collector bus of the PV plant by 35 kV cables, and the PV plant is stepped up to connect to the 220 kV AC series compensated transmission lines by the main transformer of the PV plant. Both the transformers of PV unit (0.48 kV/35 kV) and the plant (35 kV/22 kV) adopt the Y–Y grounded connection form. The parameters of series compensation transmission line are as follows: positive sequence resistance 0.03828 \( \Omega/km \), positive sequence reactance 0.3279 \( \Omega/km \), and length of 136 km.

In this paper, we focus on the transient fault ride-through performance of the PV plant connected by transmission lines with different series compensation levels to the AC system. The three-lines-to-ground fault is applied at the terminal of the series compensated line connected to this PV plant when the simulation is run for 3.0 s and the fault duration is 0.01 s. The measurements are taken at the point of common coupling (PCC), as shown in Fig. 9.

SCR is defined as the ratio of the bus short-circuit capacity to the total MW rating of the PV plants connected with the bus [1]. Based on this definition, SCR is given by

\[ \text{SCR} = \frac{S_{\text{SCMVA}}}{S_{\text{RMW}}} \]  

where \( S_{\text{SCMVA}} \) (short circuit megavolt ampere) is the short-circuit capacity at the bus in the connection with the PV plants; \( P_{\text{RMW}} \) (rating megawatt) is the rating MW of the PV plants connected with the bus.

If there is no series compensation capacitor, the transmission power of the line can be expressed as

\[ P = U_1U_2 \sin \delta/X_L = P_m \sin \delta \]  

In (6), \( U_1, U_2 \) are the voltages of starting and ending points of the line, respectively, \( X_L \) is the line reactance, \( \sigma \) is the power angle, and \( P_m \) is limit transmission power for the line. The function of series compensation capacitor is equivalent to shortening the electrical distance of the line and improving the stability limit and transmission capacity of the transmission line. \( X_C \) is the capacitance of series compensation capacitor. The parameters of series compensation transmission line are as follows: positive sequence resistance 0.03828 \( \Omega/km \), positive sequence reactance 0.3279 \( \Omega/km \), and length of 136 km.

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3.1 Different levels of series compensation condition

In this section, the simulation is implemented under different series compensation levels ($K_c = 0, 40\%, 60\%$) and constant strength of AC system ($\text{SCR} = 4$). The results of the simulation are presented in Fig. 10. The active power, reactive power, voltage, and current at the PCC are plotted in Figs. 10a–d. As Fig. 10 shows, the sub-synchronous component can be obviously observed in the system when the series compensation is used. However, the focus of this paper lies in the fault ride-through performance of the PV power plant.

It can be observed from Fig. 10a that the drop nadir of the active power decreases with the increase of the series compensation levels. It is also observed from Fig. 10b that the performance of active

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![Fig. 10 Simulation results at $K_c = 0, 40\%$ and $60\%$ scenarios](image1)

![Fig. 11 Simulation results at SCR = 2 and 6 scenarios](image2)

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power is greatly changed due to use of the series compensation. Under the condition without series compensation, the reactive power rises rapidly and then returns to steady state. When the series compensation is used, the reactive power anti-phase drop to the nadir before the rapid rise and the oscillation damping of the reactive power lightly decreases with the increase of the series compensation levels.

Also, it can be seen from Fig. 10c that the fluctuation amplitude of PCC-voltage decreases with the increase of the series compensation level, and the time from the transient state to the steady state is shortened. As can be seen in Fig. 10d, use of series compensation significantly reduces the transient overcurrent and improves the fault ride-through performance of the PV plant.

In general, the series compensation has a significant effect on the operating performance of PV power plants. The series compensation can not only enhance the transmission capacity of the line, but also improve the fault ride-through performance of the PV power plant. The transition time is reduced and the stability of the system is improved. It is interesting that series compensation can improve the fault ride-through performance of the PV plant. The mechanism of improvement needs to be deeply investigated.

3.2 Different strengths of AC system condition

In this section, the simulations are implemented for the AC system with different SCRs (SCR = 2, 6) and constant series compensation level (Kc = 40%). The results are presented in Fig. 11.

It is observed from Figs. 11a and b that the transient amplitudes of the active power and the reactive power in the system with SCR = 6 decreases 1/2 of that in the system with SCR = 6. It is also observed from Figs. 11c and d that the transient amplitudes of voltages and currents decrease with the increase of SCR. Similarly, it can be concluded that the increase in the strength of the grid can improve the stability of the entire system, shorten the transient time and facilitate the low-voltage through of the PV power plant.

4 Conclusion

In this paper, a comprehensive analysis of the operation performance of PV plant with series compensated line is presented in two scenarios: different levels of series compensation and different strengths of AC system. It can be concluded that:

(i) For the scenarios with different series compensation level, the fluctuation amplitudes of PCC active and reactive powers, and voltage, and current decrease with the increase of the series compensation levels. In addition, the transition time for the fault-through is shortened in these cases with series compensation. Therefore, series compensation can effectively improve the fault ride-through performance of the PV power plant. It is interesting that the fault ride-through performance of PV plants is improved by series compensation. The mechanism of the improvement for fault-through needs to be investigated under the condition with series compensation.

(ii) With the increase of the strengths of AC system, the system performance is also improved. The voltage fluctuation is suppressed and the overcurrent is reduced. Similarly, the increase of the strength of the grid can improve the stability of the entire system and fault ride-through performance.

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