Coordinated Control Strategy of Flexible HVDC Transmission based on New Energy Grid Connection (Postprint)

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Date: 2022-11-17T00:00:00+00:00

Abstract

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Full Text

Preamble

Coordinated Control Strategy of Flexible HVDC Transmission for New Energy Grid Integration

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Abstract: To improve the quality of photovoltaic power injected into the grid, this paper proposes a VSC-HVDC grid-connected scheme based on a coordinated control strategy using micro-synchronous phasor measurement units (P-MUs). A four-terminal topology for photovoltaic power plants integrated via VSC-HVDC is designed, and a MATLAB/Simulink model of two photovoltaic plants connected through VSC-HVDC is developed. Simulations under varying light intensity, plant outage conditions, and grid voltage disturbances demonstrate that system voltage, power, and AC-side frequency maintain stable operation, verifying the feasibility and effectiveness of the transmission scheme while enhancing grid stability and power quality.

Keywords: Photovoltaic power generation; VSC-HVDC; constant AC voltage control; DC voltage control; PQ control

1 Introduction

As photovoltaic power generation technology matures, installed capacity in China continues to increase. However, photovoltaic generation is vulnerable to environmental factors such as light intensity and temperature, leading to intermittent and fluctuating active power in the power system. High penetration rates impact power systems through grid voltage fluctuations, power flow variations, harmonics that degrade power quality, poor frequency regulation that increases overfrequency risk, and challenges related to peak output characteristics, low energy yield, and high costs of full consumption.

Current photovoltaic transmission primarily relies on local grid connection, yet local grids struggle to accommodate large-scale photovoltaic power. Direct grid connection severely impacts power flow and degrades power quality. Flexible HVDC transmission technology based on voltage source converters (VSC) enables independent control of active and reactive power, asynchronous grid connection, urban DC transmission and distribution, island power supply, flexible control, large transmission capacity, and long-distance transmission, playing a significant role in new energy integration.

This paper designs a grid-connected photovoltaic power station scheme via VSC-HVDC to achieve long-distance photovoltaic power transmission. An improved coordinated control strategy based on micro-synchronous phasor measurement units (PMU) is proposed. When active power and DC voltage fluctuate, the system automatically adjusts to restore balance, maintaining stable operation and improving grid-connected power quality.

2 System Structure for Photovoltaic Grid Connection via Flexible DC

2.1 System Topology

Figure 1 [Figure 1: see original paper] illustrates the topology of a photovoltaic power station connected to the grid through a flexible DC transmission system. The system comprises two photovoltaic power stations, two rectifier stations at the photovoltaic side (VSC1, VSC2), and two inverter stations (VSC3, VSC4). The two photovoltaic stations connect in parallel to collect electrical energy, which is transmitted to VSC3 and VSC4 terminals and then distributed to each receiving-end grid and load through control strategies.

Figure 1. VSC-HVDC system grid-connected topology

2.2 VSC System Structure and Mathematical Model

Figure 2 [Figure 2: see original paper] shows the VSC system structure. The two-level topology consists of six arms, each comprising an IGBT and a reverse-parallel diode.

Based on Kirchhoff's laws, the mathematical model of the HVDC system can be established in the three-phase static ABC coordinate system:

$$\begin{cases} L\frac{di_a}{dt} = U_{sa} - U_a - Ri_a \\ L\frac{di_b}{dt} = U_{sb} - U_b - Ri_b \\ L\frac{di_c}{dt} = U_{sc} - U_c - Ri_c \end{cases}$$

where L and R are the equivalent reactance and resistance of the converter, respectively; U_{sa}, U_{sb}, U_{sc} and i_a, i_b, i_c are the three-phase voltage and current of the power grid, respectively; and U_a, U_b, U_c are the three-phase voltages at the converter station input side. When the power grid is balanced, these equations hold.

Applying the Park transform to equation (1) yields the mathematical model of the VSC AC side in synchronous rotating coordinates. The Park transformation matrix P and its inverse matrix P^{-1} are as follows:

$$P = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix}$$

$$P^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix}$$

where θ is the angle between the d-axis and a-axis. Substituting equations (3) and (4) into equation (1) yields the voltage equations. Using a feedforward compensation decoupling control strategy, the control equations can be obtained:

$$U_d = U_{sd} - Ri_d + \omega Li_q + K_{pd}(I_{dref} - i_d) + K_{id}\int(I_{dref} - i_d)dt$$

$$U_q = U_{sq} - Ri_q - \omega Li_d + K_{pq}(I_{qref} - i_q) + K_{iq}\int(I_{qref} - i_q)dt$$

where K_{pd}, K_{id} and K_{pq}, K_{iq} are the proportional-integral coefficients of the d-axis and q-axis, respectively. From equation (6), the inner-loop decoupling controller based on the d-q synchronous rotating coordinate system can be derived, as shown in Figure 3 [Figure 3: see original paper].

Figure 3. Inner-loop current decoupling control

In the synchronous rotating coordinate system, the instantaneous active power P and reactive power Q absorbed by the converter are:

$$P = \frac{3}{2}(U_{sd}i_d + U_{sq}i_q)$$

$$Q = \frac{3}{2}(U_{sq}i_d - U_{sd}i_q)$$

When the grid voltage is oriented to the d-axis in the synchronous rotating coordinate system, $U_{sd} = U_s$ and $U_{sq} = 0$. The active and reactive power input from the grid to the VSC then become:

$$P = \frac{3}{2}U_s i_d$$

$$Q = -\frac{3}{2}U_s i_q$$

Equation (8) shows that active and reactive power can be controlled independently by controlling i_d and i_q, achieving decoupled control.

3 Coordinated Control Strategy

3.1 Analysis of VSC Operation Characteristics

Figure 4 [Figure 4: see original paper] shows the VSC-HVDC diagram. U_s and U_c are the fundamental components of the AC bus voltage and VSC input voltage, respectively; i is the fundamental current of VSC input; P_{dc}, Q_{dc}, I_{dc}, and U_{dc} are the active power, reactive power, DC line current, and DC system voltage of the DC system, respectively.

Figure 4. VSC-HVDC diagram

When the rectifier-side VSC operates normally, its input side can be equivalent to a voltage source, with the equivalent circuit shown in Figure 5 [Figure 5: see original paper].

Figure 5. VSC AC-side equivalent circuit

Ignoring the commutation reactance and equivalent loss resistance in the VSC, equation (9) can be obtained:

$$P = \frac{U_s U_c}{X} \sin\delta$$

$$Q = \frac{U_s(U_s - U_c \cos\delta)}{X}$$

where δ is the phase angle difference between U_s and U_c. Since the power angle difference δ is very small, it can be approximated as $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. From equation (9), the active power-angle droop control formula can be derived:

$$\delta = \delta_0 + k(P_{ref} - P)$$

where k is the droop coefficient; δ_0 and δ are the given reference value and steady-state operation value of the phase angle, respectively; and P_{ref} and P are the given power value and actual measured power value, respectively.

According to equation (9), the magnitude and direction of reactive power Q can be directly controlled by regulating the amplitude and phase of U_c. The magnitude and direction of active power are determined by the power angle δ. When $\delta > 0$, the VSC operates in rectification mode, absorbing active power from the AC grid; when $\delta < 0$, it operates in inverter mode, outputting power to the AC system. The magnitude and direction of active power P can be controlled by changing the phase angle δ. PWM technology can simultaneously control the modulation ratio M and phase angle δ, enabling the VSC to control active and reactive power independently. By adopting appropriate control modes at each converter station terminal, the system can maintain stable operation.

Figure 6 [Figure 6: see original paper] shows the fundamental vector diagram of VSC in steady-state operation.

Figure 6. VSC fundamental wave vector diagram

3.2 Coordinated Control Strategy

Figure 7 [Figure 7: see original paper] shows the simplified VSC-HVDC equivalent structure diagram. Since the amplitude of the power angle difference δ is small, a micro-synchronous phasor measurement unit (PMU) is introduced to measure δ. PMU enables real-time measurement of voltage and current phasors in power system transmission lines with high time accuracy at the microsecond level. Measurement data is transmitted to the δ controller through GPS or Beidou time synchronization, precisely regulating system active power output through δ to maintain stability.

The intermittency and randomness of photovoltaic power generation cause significant fluctuations in DC voltage and system power. To ensure stable operation and improve transmission quality, an improved coordinated control strategy based on micro-synchronous phasor measurement units is proposed. The control structure for the photovoltaic power station side is shown in Figure 8 [Figure 8: see original paper].

Figure 8. Improved station control structure diagram

Drawing on the concept of margin control, the outer-loop voltage controller is designed as shown in Figure 9 [Figure 9: see original paper].

Figure 9. Improved outer-loop control principle structure diagram

In the diagram, U_{dcmax} and U_{dcmin} are the given maximum and minimum reference values of DC voltage; PI1 and PI3 are the low-order and high-order regulators of DC voltage; PI2 is the P-δ droop control regulator; and X_1, X_2, and X_3 are the output values of PI1, PI2, and PI3, respectively.

The PI2 control mode is designed as:

$$X_2 = K_{p2}\Delta\delta + K_{i2}\int \Delta\delta dt + K_{p2}\Delta P + K_{i2}\int \Delta P dt$$

where K_{p2} and K_{i2} are the proportional and integral coefficients of the PI2 controller, respectively. In Figure 7, at point N, PMU measures δ in real time and transmits the data to the signal receiver at the converter station side to calculate $\Delta\delta$. Power is obtained by measuring voltage and current, and X^* is calculated using droop formula (10). $\Delta\delta$ and ΔP are input to the PI2 controller to obtain the d-axis reference value I_{dref} of the inner-loop current, which then generates the PWM reference value to produce trigger pulses for PWM modulation, achieving DC voltage and power regulation.

To ensure stable operation under extreme environmental conditions, the system can switch to constant DC voltage control based on system fluctuations. The output of each PI controller satisfies the following requirements:

$$X = \begin{cases} X_1 & \text{if } U_{dc} > U_{dcmax} \\ X_2 & \text{if } U_{dcmin} \leq U_{dc} \leq U_{dcmax} \\ X_3 & \text{if } U_{dc} < U_{dcmin} \end{cases}$$

The logical relationship is as follows: According to equation (13), when the converter station operates normally, the controller output X is determined by X_2, i.e., $X = X_2$. The outputs of VSC1 and VSC2 station controllers in normal operation are determined by the P-δ droop controller. According to the droop coefficient, when photovoltaic active power output fluctuates, the phase angle δ changes. Through the droop curve, the VSC power injected into the DC system is adjusted to maintain stable operation. The P-δ characteristic curve is shown in Figure 10 [Figure 10: see original paper].

Figure 10. P-δ characteristic curve

During normal operation, the VSC of the converter station can fluctuate with small amplitude in the droop characteristic region. DC voltage fluctuation is generated by charging and discharging of the DC-side capacitor in the converter station when the actual voltage deviation reaches the preset value. If the VSC operates in P-δ droop control mode and the entire DC system experiences power surplus or shortage, the DC voltage continuously rises or falls. The relationship between power variation ΔP and DC voltage change ΔU is shown in equation (14):

$$\Delta P = CU_{dc}\frac{dU_{dc}}{dt}$$

System power balance can be stabilized by adjusting DC voltage.

When a fault occurs on the grid side, the DC transmission system reduces power delivered to the AC grid to achieve low-voltage ride-through, causing power accumulation and DC voltage increase. At this time, the VSC4 station switches to current-limiting control mode for self-protection.

The inner-loop controller of each converter station adopts feedforward compensation decoupling control as shown in Figure 3 to achieve PWM control. Table 1 presents the coordinated operation switching table for each terminal.

Table 1. Coordinated control operation switching table of each station

4 Simulation Analysis

4.1 System Control Structure

Based on the control strategy for each terminal, the overall control principle structure diagram can be summarized as shown in Figure 11 [Figure 11: see original paper]. The phase-locked loop (PLL) provides reference phase for trigger generation and voltage vector control. The outer-loop voltage controller compares the actual measured value with the given reference value, and after PI regulation, enters the inner-loop circuit to achieve DC voltage and active power control.

Figure 11. Control system structure diagram

In MATLAB/Simulink simulation software, a four-terminal transmission system model of photovoltaic power stations connected to the grid via flexible DC transmission is built. MPPT control is adopted in both photovoltaic power stations to maintain maximum active power output. The DC voltage, power, and AC-side frequency of the system under three conditions are simulated with initial light intensity $S = 800\,\mathrm{W/m^2}$ and temperature $T = 25°\mathrm{C}$.

4.2 Simulation Results and Analysis

Condition 1: Photovoltaic power station 1 increases light intensity from $S = 800\,\mathrm{W/m^2}$ to $S = 1000\,\mathrm{W/m^2}$ at 0.8 s and shuts down at 2 s. Photovoltaic station 2 decreases light intensity from $S = 800\,\mathrm{W/m^2}$ to $S = 200\,\mathrm{W/m^2}$ at 1.4 s. As shown in Figure 12 [Figure 12: see original paper], the system DC voltage and frequency experience small-amplitude fluctuations at 0.8 s and 1.4 s, lasting approximately 0.1 s. Compared with traditional control, the DC voltage fluctuation amplitude is significantly reduced. The active power output of photovoltaic power station 1 increases from 1.5 MW to 1.875 MW at 0.8 s, while station 2 decreases from 0.5 MW to 0.125 MW at 1.4 s. The total active power output changes from 2 MW → 2.375 MW → 2 MW. The passive network continuously absorbs 0.4 MW from the DC system. The grid-connected system power variation is 1.6 MW → 1.975 MW → 1.6 MW. The system DC voltage, power, and frequency quickly reach stable operation.

At 2 s, the active power output of photovoltaic power station 1 drops to 0, reducing total photovoltaic generation from 2 MW to 0.125 MW. The grid-connected power decreases from 1.6 MW to -0.275 MW, while the passive network continuously absorbs 0.4 MW from the DC system. The system DC voltage decreases slightly at 2 s, with amplitude within allowable deviation range and duration of approximately 0.1 s, demonstrating more stable coordination control than traditional methods. Simulation results show that the system maintains stable operation when active power output changes and one photovoltaic station shuts down.

(a) DC voltage waveform
(b) Power waveform at each end
(c) Frequency waveform of AC side at each end

Figure 12. System simulation waveform under light intensity change and single-end outage

Condition 2: Both photovoltaic power stations shut down at 1 s and restore power supply to the DC system at 1.5 s. Compared with traditional control, the active power of the PV system decreases from -0.4 MW to -1.5 MW. The PV system-side and grid-side frequencies fluctuate significantly at 1 s, but the amplitude remains within allowable frequency deviation, with duration of approximately 0.1 s.

At 1.5 s, power plant 1 resumes transmitting power to the DC system with a transient transition time of about 0.15 s. The power grid gradually recovers to absorb power from the DC system, and the passive network begins receiving power from the photovoltaic station. The DC voltage and frequency at each terminal fluctuate slightly for 0.05 s. Simulation results demonstrate that the DC system can still be maintained by the AC power grid when all photovoltaic power stations are out of operation.

(a) DC voltage waveform

(b) Power waveform at each end
(c) Frequency waveform of AC side at each end

Figure 13. System simulation waveform when all photovoltaic power plants are out of operation

Condition 3: From 0.8 s to 1.2 s, the phase-a grid voltage drops to 50%. As shown in Figure 14 [Figure 14: see original paper], phase-a voltage drops instantaneously to 50% at 0.8 s, while the system DC voltage remains essentially stable with minimal fluctuation. At 0.8 s and 1.2 s, the grid-connected power fluctuates slightly, and the PV plant output power remains unchanged within allowable margins. The grid-side frequency is almost unaffected and maintains stable operation. At 1.2 s, the fault is cleared and the system quickly returns to stable operation.

From 1.6 s to 2 s, the phase-b grid voltage is set to 1.2 pu. As shown in Figure 14(a), phase-b voltage rises to 1.2 times rated voltage at 1.6 s. At this time, the DC voltage, grid-connected power, and grid frequency remain almost unaffected and maintain stable operation. Simulation results show that the transmission system possesses certain high- and low-voltage ride-through capability.

(a) Grid voltage waveform
(b) DC voltage waveform
(c) Power waveform at each end
(d) Frequency waveform at each end

Figure 14. Simulation waveform of three-phase short-circuit fault in the power grid

5 Conclusion

Based on photovoltaic power generation characteristics and the advantages of coordinated control strategies, this paper studies and analyzes the grid-connected system model of two photovoltaic power stations through VSC-HVDC, coordinating control strategies at each terminal to improve system stability and power quality.

When light intensity changes, the active power output of photovoltaic stations varies. The receiving-end station can quickly adjust power absorption and rationally distribute electrical energy, enabling power balance at each system terminal and maintaining stable operation. When the photovoltaic system shuts down, system voltage and power remain essentially unaffected. The power grid rationally distributes receiving-end power absorption, with DC voltage, power, and frequency fluctuations at each terminal within allowable deviation ranges.

During grid-side voltage fluctuations, photovoltaic power stations can achieve high- and low-voltage ride-through and return to normal operation after grid voltage stabilizes, avoiding power flow oscillations caused by photovoltaic system shutdown due to grid transient faults. From the transient process perspective, the system response speed is faster, grid-connected power and DC voltage fluctuations are reduced, transient response time is significantly shortened, and system stability is improved. From the AC-side frequency perspective, when power and voltage fluctuate significantly, the AC frequency remains almost unaffected, harmonics are suppressed, and power quality is improved.

With continuous increases in photovoltaic power generation capacity, this control strategy provides a theoretical basis for future integration of larger photovoltaic generation capacity and offers a research direction for control strategies of larger-capacity, more complex power generation systems.

References

FLOURENTZOU. N, AGELIDIS. V.G, DEMETRIADES .G.D, et al. (2019) VSC-based HVDC power transmission systems: an overview. IEEE Transactions on Power Electronics, 24(3): 592-602.

Guangfu Tang., Luo Xiang. & Wei Xiaoguang. (2013). Multi-terminal DC Transmission and DC Grid Technology[J]. Chinese Journal of Electrical Engineering, (10):8-17.

Weimin Ma., Fangyu Wu., & Yiming Yang., et al. (2014) Analysis of the status and application prospects of flexible HVDC transmission technology[J]. High Voltage Technology, 40(8):2429-2439.

LU W X. & OOI B T. (2003). DC overvoltage control during loss of converter in multiterminal voltage-source converter-based HVDC[J]. IEEE Transactions on Power Delivery, 18(3): 915-920.

Dianguo Xu., Yuchao Liu. & Jian Wu. (2015). Summary of Research on Control of Multi-terminal HVDC Transmission System [J]. Journal of Electrical Engineering and Technology, 30(9):1-12.

Shu Y., Tang G. & Pang H. (2019). Study on Yu'e back-to-back VSC-HVDC system[J]. CSEE Journal of Power and Energy Systems.

Li Yangman. (2019). Research on the control strategy of VSC-HVDC transmission system applied to wind power grid connection[D]. Harbin Institute of Technology.

Xu Zheng. (2013). Flexible DC transmission system [M]. China Machinery Industry Press.

Guoliang Zhou. (2009). Research on Control Strategy of HVDC Transmission System Based on Voltage Source Converter [D]. North China Electric Power University(Hebei).

Chen Hairong. (2007). Research on the control and protection strategy of VSC-HVDC system when AC system fails[D]. Zhejiang University.

Ren Minghui. (2017). Research on coordinated control method of multi-terminal flexible DC transmission system [D]. University of Electronic Science and Technology of China.

Lei Wang., Xiaolong Wu. & Junxian Hou, et al. (2019). Control of photovoltaic grid-connected multi-terminal flexible DC power transmission[J]. Power System Protection and Control, 47(04): 65-72.

Majumder R., Ghosh A. & Ledwich G., et al. (2009). Angle droop versus frequency droop in a voltage source converter based autonomous microgrid[C]// IEEE Power & Energy Society General Meeting. IEEE.

Weiran Zhao., Guanghui Li. & Guoqing He., et al. (2012) VSC-HVDC grid-connected topology of photovoltaic power plants and its control strategy[J]. Grid Technology, 36(11): 41-45.

Xu Yin., Wang Sijia., Wu Xiangyu., Wang Jinli. & Fang Chen. (2019). Multi-source collaborative control method of distribution network islands based on synchronous phasor measurement[J]. Power System Technology, 43(03): 872-880.

Xu Shukai., Xie Xiaorong. & Xin Yaozhong. (2005). Application status and development prospects of wide area measurement system based on synchronous phasor measurement technology [J]. Power System Technology, (02): 44-49.

De L R J., Centeno V. & Thorp J S., et al. (2010). Synchronized Phasor Measurement Applications in Power Systems[J]. IEEE Transactions on Smart Grid, 1(1):20-27.

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