



# Article An Improved Coordinated Control Strategy for PV System Integration with VSC-MVDC Technology

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**Abstract:** The rapid development of renewable energy calls for feasible and reliable technologies to transmit and integrate power into grids. Voltage Source Converter (VSC)- Direct Current (DC) technology is considered as a promising solution for its independent control of active and reactive power. Modeling and coordinated control of a large-scale concentrating photovoltaic integration system with VSC-MVDC (Voltage Source Converter-Medium Voltage Direct Current) technology have been investigated in this paper. The average controlled-source model of PhotoVoltaic (PV) integration system is firstly established. Then, a novel control strategy without fast communication is proposed to improve the reliability of the coordinated control system. An extra voltage loop is added to the basic control block, which is able to assure stable operation of the PV system in various conditions. Finally, the proposed control strategy is verified with simulation results.

**Keywords:** coordinated control strategy; MVDC (Medium Voltage Direct Current); PV (PhotoVoltaic); VSC (Voltage Source Converter)

# 1. Introduction

The combination of Voltage Source Converter (VSC) and Direct Current (DC) transmission technology has attracted the interests of researchers and power grid operators recently. DC transmission system has lower loss and higher capacity than the Alternating Current (AC) system. Although the investment cost of converter station in DC transmission system is much higher than in an AC transmission system, the advantages of the DC transmission system are superior to AC transmission system when the transmission distance is long enough [1].

As the majority of equipment in existing power grids is AC generators and AC loads, converters are needed among AC and DC system. Another role of converters in DC system is to connect and transmit power between different DC voltage levels, just like transformers in AC system.

Current Source Converter (CSC) and VSC are two basic types of converters widely used in AC/DC systems. Thyristor-valves are usually used in CSC, which relies on AC system to achieve commutation. It is also known as Line Commutated Converter (LCC). VSC adopts fully controlled power electronic devices as basic switches, which shows superiority in rapid and independent control of active and reactive power and ability to feed weak AC system with less risk of commutation failures over LCC [2,3].

Given the advantages, VSC-DC technology is regarded as a solution to bulk power transmission over long distances and offshore renewable energy integration. Many VSC-DC based projects have been built around the world in order to integrate offshore wind energy [4], connect asynchronous AC systems, and power offshore platforms [5].

Solar energy is one kind of clean and renewable energy, which has been significantly developed in the past decades. There are two patterns of PV generations. The first pattern is dispersed installation with Low Voltage (LV) integration and local consumption, and the second one is large-scale centralized installation with Medium/High Voltage (MV/HV) integration and remote consumption [6]. Because of the fluctuations of solar energy, VSC-MVDC/HVDC system with rapid power flow control characteristic is usually employed when large-scale PV system is integrating into grids.

This paper investigates a large-scale concentrating PV system integrated into a power grid with VSC-MVDC (Medium Voltage DC) technology. The power generated by PV arrays is allocated by DC/DC converter, transmitted to load center with MVDC bus, and integrated to AC system with DC/AC converter. There are lots of power electronic devices in VSC-MVDC system. Time domain simulation is very time consuming with the detailed device-level model. Average modeling is an effective method to simplify model complexity so as to accelerate simulation [7]. Simulation time can be significantly reduced while keeping the same controller structure. It is time-efficient to use the average model when a system-level control is under investigation, in which the dynamic behavior of equipment is not the priority.

DC voltage is an important indicator of system stability in DC networks. As there are multiple DC voltage buses in the PV-MVDC system, voltages at different DC buses should be controlled coordinately to assure stable and safe operation of the system. An improved coordinated control scheme with a higher system reliability is proposed in this paper, which can keep DC voltages stable under normal operation and power limit conditions without reliance on the fast communication system. The average controlled-source models of converters in PV system are employed to investigate the effectiveness of this control scheme. Time domain simulation results in MATLAB/Simulink indicate the superiority of the proposed control scheme by comparison with the basic conventional control scheme.

#### 2. System Topology and Model

Figure 1 shows the system configuration of a PV integration system. A number of PV panels are connected in series and parallel into a PV array to generate the desired voltage and current. An isolated DC/DC converter is used to step up the voltage. To achieve Maximum Power Point Tracking (MPPT), a boost converter is connected between PV array and isolated DC/DC converter. The MVDC bus allocates the solar power and transmits it to a DC/AC converter to feed AC power system. When two more converters are connected to an MVDC bus, a Multi-Terminal DC (MTDC) system is formed.

In Figure 1, the number of full-bridge isolated DC/DC converters connected to MVDC bus is M, and the number of boost converters connected to isolated DC/DC converter bus is N. The DC voltage at MVDC bus is  $U_{dc0}$ , the DC voltage and current at primary side of *i*th full-bridge isolated DC/DC converter is  $U_{dci}$  and  $I_{dci}$ , and the DC voltage and current at primary side of *ij*th boost converter is  $U_{dcij}$  and  $I_{dcij}$ . In the following contents, a subsystem composed of the *ij*th PV array, the *ij*th boost converter, the *i*th full-bridge isolated DC/DC converter, the DC/AC converter, and the AC system is selected for analysis and explanations (i = 1, ..., M, j = 1, ..., N).

#### 2.1. PV Panel and Boost Converter

Figure 2 shows the characteristics of PV array and its widely used single diode equivalent circuit model, a combination of an ideal current source sensitive to sunlight, a diode in parallel connection, a parallel resistance  $R_p$ , and a series resistance  $R_s$  [8]. The relationship between output voltage ( $U_{pv}$ ) and current ( $I_{pv}$ ) of PV panel is shown as follows.

$$I_{pv} = I_{ph} - I_0 \left\{ \exp\left[\frac{q(U_{pv} + R_s \cdot I_{pv})}{N_s \cdot k \cdot T \cdot A}\right] - 1 \right\} - \frac{U_{pv} + R_s \cdot I_{pv}}{R_p}$$
(1)

where  $I_{ph}$  is the PV current,  $I_0$  is saturation current, q is the electron charge (1.60217646 × 10<sup>-19</sup> C),  $N_s$  is the number of PV cells in series, k is the Boltzmann constant (1.3806503 × 10<sup>-23</sup> J/K), T (in Kelvin) is the temperature, and A is the diode ideality constant.



Figure 1. PhotoVoltaic (PV) integration system with VSC-MVDC technology.



Figure 2. (a) PV array characteristic; (b) PV array model.

As shown in Figure 2a, there is a Maximum Power Point (MPP) in the power-voltage curve of PV panel. To improve the efficiency of PV panel, a boost converter is used to achieve MPPT. Boost converter acts as an impedance adjuster by changing duty-cycle of the control signal to match PV panel and load impedance under different atmospheric conditions. So far, several MPPT algorithms have been proposed in the literature, and they are categorized into five groups, including tracking techniques with constant parameters, with measurement and comparison, with trial and error, with mathematical calculation, and with intelligent prediction [9].

Incremental conductance method is used in [10]. MPP is reached when  $dP_{pv}/dU_{pv}$  equals to zero, which can be located by comparing the instantaneous conductance  $(I_{pv}/U_{pv})$  to the incremental conductance  $(\Delta I_{pv}/\Delta U_{pv})$ , i.e.,

$$\frac{dP_{pv}}{dU_{pv}} = \frac{d(U_{pv} \cdot I_{pv})}{dU_{pv}} = I_{pv} + U_{pv}\frac{dI_{pv}}{dU_{pv}}$$
(2)

The average model of the boost converter is shown in Figure 3b, in which a controlled current source and a controlled voltage source are used to replace the complex semiconductor switches. The voltage across semiconductor switch S ( $U_{ao}$ ) satisfies

$$U_{ao} = \begin{cases} 0 & t \in [0, D_{ij} \cdot T_s) \\ U_{bo} & t \in [D_{ij} \cdot T_s, (1 - D_{ij}) \cdot T_s] \end{cases}$$
(3)

where  $U_{bo}$  is the output voltage,  $D_{ij}$  is the duty cycle, and  $T_s$  is the period of the carrier.



**Figure 3.** (**a**) Boost converter topology; (**b**) Average model of boost converter; and, (**c**) Controller design of boost converter.

Power balance formula is the tie of the input side and output side of a boost converter. So the current of the controlled current source ( $I_b$ ) is expressed as

$$I_{\rm b} = \frac{U_{\rm ao} \cdot I_{\rm a}}{U_{\rm bo}} \tag{4}$$

where  $I_a$  is the current of the controlled voltage source. The reference direction of these measurements is shown in Figure 3b.

The controller of the boost converter is shown in Figure 3c. The reference voltage of PV array,  $U_{dcij\_ref}$ , is offered by MPPT controller. The outer voltage controller generates reference current ( $I_{dcij\_ref}$ ) for the inner current controller, and the inner current controller produces duty cycle of the control signal ( $D_{ij}$ ) for the semiconductor switches. For the detailed model, the duty cycle  $D_{ij}$  needs to be transformed into trigger pulses by PWM (Pulse Width Modulation) block. For the average model,  $U_{ao}$  is controlled by  $D_{ij}$  according to function (3).

#### 2.2. Full-Bridge Isolated DC/DC Converter

Full-bridge isolated DC/DC converter is used to step up voltage so as to match MVDC bus [11,12]. The fully-controlled H-bridge is used to invert DC voltage to AC voltage, the high-frequency transformer is used to provide galvanic isolation and step up voltage, and uncontrolled H-bridge is used to rectify AC voltage to DC voltage, as shown in Figure 4. Semiconductor switches S1 and S4 are controlled by identical gating signal, so do S2 and S3. A pair of gating signal shifted by 180° in phase with the duty-cycle greater than 50% is sent to S1 (S4) and S2 (S3). There is an overlap of gating signals of S1 (S4) and S2 (S3), as shown in Figure 5 (t1~t2 and t3~t4). During this interval, all four switches are inducted

on, and energy is stored in inductor L. During t0~t1 (or t2~t3), S2, and S3 (or S1 and S4) are turned off, and the voltage at the primary side of transformer T ( $u_{cd}$ ) is boosted.



**Figure 4.** (a) Full-bridge isolated Direct Current (DC)/DC converter topology; (b) Average model of full-bridge isolated DC/DC converter; and, (c) Controller design of full-bridge isolated DC/DC converter.



Figure 5. Steady-state operating waveforms of full-bridge isolated DC/DC converter.

The current of transformer T at primary side  $(i_c)$  is given by

$$i_{c} = \begin{cases} 0 & t \in [t1, t2) \text{ or } [t3, t4] \\ I_{a} & t \in [t0, t1) \\ -I_{a} & t \in [t2, t3) \end{cases}$$
(t3 - t2) = (t1 - t0) = (1 - D\_{i})T\_{s}   
(t2 - t1) = (t4 - t3) = (D\_{i} - \frac{1}{2})T\_{s}(5)

where  $I_a$  is the current of the controlled voltage source and  $D_i$  is the duty cycle.

The voltage across a and b,  $U_{ab}$ , is expressed as follows, according to the principle of power conservation. The reference direction of these measurements is shown in Figure 4b.

$$U_{\rm ab} = \frac{u_{\rm cd} \cdot i_{\rm c}}{I_{\rm a}} \tag{6}$$

The controller of full-bridge isolated DC/DC converter is shown in Figure 4c, which is similar to the controller of the boost converter in Figure 3c.

#### 2.3. DC/AC Converter

Modular Multilevel Converter (MMC) is preferred in high power applications for its small converter footprint, high ac-side current quality, and robustness through the use of redundant sub-modules [13]. Neglecting the complex process of semiconductor switches, the average model of MMC is established, as shown in Figure 6b.



**Figure 6.** (a) DC/Alternating Current (AC) topology; (b) Average model of DC/AC; and, (c) Controller design of DC/AC converter.

The controlled voltage source voltage  $u_i$  (j = a, b, c) is given by

$$u_j = u_{j\_\text{ref}} \quad j = a, b, c \tag{7}$$

where  $u_{j_{ref}}$  is the reference voltage offered by the inner current controller.

The current at DC side  $(I_d)$  is expressed as follows, also according to the principle of power conservation.

$$I_{\rm d} = \frac{\sum u_j \cdot i_j}{U_{\rm de}} \quad j = a, b, c \tag{8}$$

where  $U_{de}$  is the voltage of MMC at DC side.

The controller of DC/AC converter is shown in Figure 6c. To facilitate controller design, the three-phase voltage and current at Point of Common Coupling (PCC) are transformed into dq frame. By selecting different outer controller, DC/AC can operate in  $U_{dc}$ -Q mode or P-Q mode. The inner current controller adopts PI controller with current decoupled compensation and voltage feed-forward compensation to compute the reference voltage at converter-side.

#### 2.4. AC System

AC system is simplified as an ideal three phase voltage source with the specified Short Circuit Level (SCL),  $S_N$ , as shown in Figure 7.  $S_N$  is defined as

$$S_{\rm N} = \frac{U_{\rm s}^2}{2\pi f \cdot L} \tag{9}$$

where  $U_s$  and f are the Root Mean Square (RMS) voltage and frequency of three-phase voltage source at PCC, and L is the inductance of the internal impedance.



Figure 7. (a) AC grid; (b) Equivalent model of AC grid.

# 3. Coordinated Control Strategy of PV Integration System

#### 3.1. Conventional Control Scheme of PV Integration System

In system-level control with the conventional method (blue line in Figure 8), the master converter, namely DC/AC converter, operates in  $U_{dc}$ -Q mode and is responsible for controlling the stability of MVDC bus voltage ( $U_{dc0}$ ). The *i*th full-bridge isolated DC/DC converter controls the voltage at its lower side ( $U_{dci}$ ). The *i*th boost converter controls the voltage at solar panels ( $U_{dcij}$ ) to achieve MPPT. This method ensures DC buses voltage stability in normal states. However, the MVDC bus voltage is controlled only by the DC/AC converter, which is vulnerable for the safe operation of the system. PV panels operate at MPP to generate maximum power in normal states. However, if the AC system cannot consume so much power (e.g., a fault occurs in AC system), the reference DC voltage of PV panel needs to be adjusted with the aid of fast communication system, so as to reduce the power output of PV panels. The MPPT controller in the *ij*th boost converter should be blocked and boost converter should be in constant voltage mode with the voltage reference ( $U_{dcij\_ref}$ ) offered by the control center. The delay of communication system always has a negative influence on system's fast response. The communication system may also reduce the system reliability.



Figure 8. Conventional control scheme of PV integration system.

#### 3.2. Improved Control Scheme

To improve the reliability of the system, we introduce an extra DC voltage control loop into DC/DC controllers, as shown in Figure 9, with the red line.

The improved controller designs of the *ij*th boost converter and the *i*th full-bridge isolated DC/DC converter are depicted in Figure 10, and the extra loop is highlighted in red. A dead band is added to the extra voltage controller to disable the extra loop in normal states.  $\Delta U_{ij}$  and  $\Delta U_i$  are the dead bands of the *ij*th boost converter and the *i*th full-bridge isolated DC/DC converter, respectively. Signal S is a global enable signal of extra loops. When the system starts up, the extra loops should be blocked by setting S to false. When S is set to be logic one, the effectiveness of the extra loops is dependent on the measured voltage of the extra loops. Only the basic conventional control scheme takes effect if the extra measured DC voltage is in the range of the dead band. In Figure 10a,  $E_{ijMPPT}$  and  $E_{ij}$  are the enable signal of the MPPT controller and the original outer voltage loop controller in the *ij*th boost converter, respectively. In Figure 10b,  $E_i$  is the enable signal of the original outer voltage loop controller in the *ij*th boost converter.



Figure 9. Improved control scheme of PV integration system.

This improved control scheme can achieve automatic adjustment of PV power according to the indicator of DC voltages. When AC system needs to limit the power injected into the grid, the DC/AC converter will switch into *P*-*Q* control mode. The MVDC bus voltage,  $U_{dc0}$ , will then rise. When it exceeds the dead band,  $\Delta U_i$ ,  $E_i$  becomes logic zero to disable the original control blocks (encircled with blue dot line in Figure 10b).  $U_{dc0}$  will be controlled by all of *M* full-bridge isolated DC/DC converters. The primary side DC voltage of full-bridge isolated DC/DC converters,  $U_{dci}$ , will also rise. When it exceeds the dead band,  $\Delta U_{ij}$ ,  $E_{ijMPPT}$ , and  $E_{ij}$  become logic zero to freeze MPPT controller and original voltage loops (encircled with blue dot line in Figure 10a).  $U_{dci}$  will be regulated by all of *N* boost converters. DC voltage at PV panel will deviate from the voltage corresponding to MPP, and the power generated by PV panel will be reduced automatically. No communication is needed among converters in this process. As there are many DC/DC converters.  $K_{ij}$  and  $K_i$  are the droop coefficients of the *ij*th boost converter and the *i*th full-bridge isolated DC/DC converter, respectively.



**Figure 10.** (a) Improved controller design of boost converter *ij*; (b) Improved controller design of full-bridge isolated DC/DC converter *i*.

### 4. Simulation and Results

The average-value model of PV system, as shown in Figure 11, is established in MATLAB/Simulink to verify the effectiveness of the proposed control strategy. Ten groups of 500 kWp PV panels are connected to ten boost converters, respectively. Four isolated DC/DC converters are connected to an MVDC bus. The power generated by PV panels is integrated into AC grid with one DC/AC converter. The parameters of the modeled system are listed in Table 1.

Devices	Parameters	Values
PV panel	open circuit voltage	1050 V
	short circuit current	1270 A
	maximum power point voltage	835 V
	maximum power	500 kW
Boost converter	rated power	500 kW
	rated voltage at primary side	1 kV
	rated voltage at secondary side	2 kV
Full-Bridge Isolated DC/DC converter	rated power	1 MW/1.5 MW
	rated voltage at primary side	2 kV
	rated voltage at secondary side	60 kV
DC/AC converter	rated power	5 MVA
	rated dc voltage	60 kV
	rated ac voltage	35 kV
AC system	SCL	500 MVA
	rated ac voltage	35 kV

Table 1. Parameters of the Modeled System.

The extra voltage loop controllers and MPPT controllers are not effective during 0~6 s (i.e., only basic controller are effective). For this duration, boost converter regulates the voltage at PV panel at 1.035 kV, full-bridge isolated DC/DC converter regulates the voltage at the primary side of isolated DC/DC converter at 2 kV, and DC/AC converter is in  $U_{dc}$ -Q mode and regulates MVDC bus voltage at 60 kV.



Figure 11. The PV integration system model in MATLAB/Simulink.

The extra voltage loop controller and MPPT controller are enabled at 6 s. Boost converter adjusts the voltage at PV panel dynamically to achieve MPPT. The maximum power injected to AC grid is about 4 MW, and DC voltages are kept stable in this process.

DC/AC converter switches into *P*-*Q* control mode at 15 s. The power injected to AC grid is limited to 2.5 MW. At 18 s, AC grid needs more active and reactive power support, 3 MW active power, and 1 MVA reactive power are offered from PV system.

The waveform of MVDC bus ( $U_{dc0}$ ) and power injected into AC grid ( $P_{ac}$  and  $Q_{ac}$ ) are depicted in Figure 12.  $U_{dc0}$  is regulated at 1 pu during 0~15 s. The power injected into AC grid is smoothly increased to maximum power about 4MW during 6~10 s. When DC/AC converter switches into P-Qmode at 15 s,  $U_{dc0}$  will rise and it is a signal to reduce the power generated from PV system.

The enable signal of primary side voltage control of full-bridge isolated DC/DC converter 1,  $E_1$ , is depicted in Figure 13. When  $U_{dc0}$  exceeds the dead band ( $\Delta U_1 = 0.02 \text{ pu}$ ),  $E_1$  becomes logic zero to disable the primary side DC voltage control of full-bridge isolated DC/DC converter 1. The isolated DC/DC converter 1 is then in control of MVDC bus voltage ( $U_{dc0}$ ). The switchover of the controller occurs at 15.02 s when  $U_{dc0}$  is greater than 1.02 pu.

The primary side DC voltage and power waveforms of four isolated DC/DC converters are shown in Figure 14. The DC voltages,  $U_{dc1\sim4}$ , are regulated by isolated DC/DC converters at 1 pu during 0~6 s. During 6~22 s, DC voltages,  $U_{dc1\sim4}$ , are controlled by isolated DC/DC converter 1~4 when they are in the range of 0.97~1.03 pu (the dead band is 0.03 pu). They are controlled by boost converters connected with the isolated DC/DC converter, if DC voltage exceeds the dead band.



Figure 12. DC voltage, active power and reactive power of DC/AC converter.



**Figure 13.** MVDC bus voltage and enable signal of the original voltage loop in isolated DC/DC converter 1.



Figure 14. DC voltage and power of isolated DC/DC converter 1~4.

The enable signal of primary side voltage control,  $E_{11}$ , and enable signal of MPPT control,  $E_{11MPPT}$ , of boost converter 11 are depicted in Figure 15. The primary side DC voltage and power waveforms of boost converter 11~12 are shown in Figure 16. The extra voltage controller and MPPT controller of boost converter 11 are blocked during 0~6 s. The controller of boost converter 11 regulates the voltage at PV panel 11 ( $U_{dc11}$ ) at 1.035 pu, which is very close to PV panel's open circuit voltage (1.05 pu). Extra voltage controller and MPPT controller are unblocked during 6~22 s. The dead band of extra voltage loop in boost converter 11 ( $\Delta U_{11}$ ) is set to be 0.03 pu. As shown in Figure 15,  $E_{11}$  and  $E_{11_MPPT}$  are zero during 7.08~7.66 s, and 15.23~22 s, as the secondary side voltage ( $U_{dc1}$ ) of boost converter 11 is then disabled, and boost converter 11 begins to regulate  $U_{dc1}$ .  $U_{dc1}$  is stabilized at 1.08 pu during 15~18 s, and at 1.06 pu during 18~22 s. The MPPT controller is also disabled, and PV panels operate at a higher voltage with less power output.

As two or three boost converters are connected to one isolated DC/DC converter, and four isolated DC/DC converters are connected to one DC/AC converter, droop control is used among them to avoid control conflicts. After AC/DC converter switches into *P*-*Q* control mode, the MVDC bus voltage rises and it is regulated by isolated DC/DC converter 1~4. The DC voltage at the primary side of isolated DC/DC converter will also rise and be regulated by boost converters. The droop parameter of isolated DC/DC converter 1~4 are all set to be 10, so the power change is equally shared among them. So do boost converter 11~12, 21~22, 31~33, and 41~43.

To compare the performance of the improved control strategy and the conventional control strategy, a comparative study is conducted. The communication latency is assumed to be 20 ms, i.e., when DC/AC needs to limit the power at 15 s, a signal to disable MPPT controller and adjust voltage reference at PV panels is sent to the controller of boost converters at 15.02 s. The voltage reference at PV panels is updated at 18.02 s. The waveform of MVDC bus ( $U_{dc0}$ ) and power injected into AC grid ( $P_{ac}$  and  $Q_{ac}$ ) in two cases are depicted in Figure 17. It is clear that the proposed control strategy has a faster response than the conventional method. Although the DC voltage deviates from 1 pu with the proposed control strategy, it is still in safe range to keep the system in stable operation.



**Figure 15.** Primary side DC voltage and enable signal of original voltage loop and MPPT controller in boost converter 11.



Figure 16. DC voltage and power of boost converter 11~ 12.



Figure 17. Comparison of the two control strategies.

# 5. Conclusions

VSC-MVDC technology is a promising solution for solar energy integration. As there are multiple DC buses with different voltage levels in PV integration system, coordinated control among equipment is necessary to satisfy stable and safe operation of the system. An improved coordinated control scheme without reliance on fast communication is proposed in this paper, in which DC voltage is controlled coordinately by all of the equipment connected to the DC bus. Average-value controlled source model of equipment is established in MATLAB/Simulink software. Time domain simulation results have verified the effectiveness of the proposed control scheme. It is proved that the proposed control strategy has a faster response and higher reliability than the conventional control strategy.

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