The Reactive Power Support Strategy based on Dual-loop Control for Three-phase Grid-connected Inverter

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Abstract. Renewable energy sources (RESs) generally connected with electric power system via power electronic interface. This paper presents a reactive power and voltage (Q/V) control strategy of three-phase photovoltaic (PV) system to offering reactive power based on the typical dual-loop control topology. It is worth mentioning that control strategy can support reactive power when a low voltage fault occurs in AC bus without additional compensation device. With the help of the decoupling control, the PV array can generate active power as much as possible in variable external solar radiation conditions. The voltage of PV arrays is adopted as the objective, which on account of the easy availability and controllability of voltage, to control output active power. Besides, accurately modeling process from a PV cell to PV array is described in the beginning to acquire the P-V and V-I characteristics of PV arrays, which promote the design of Q/V control.

1 Introduction

Due to the conflict of the fast development of world economy and fossil energy lacking, and climate changes caused by power generation by burning of fossil fuels, it is inevitable to develop RESs on a large scale. Converting renewable energy like solar energy, wind power, geothermal energy, and bioenergy into electrical energy is the most efficient and proven technique so far. Electrical energy is an independent and interesting transient vector that provides a great way to incorporate RESs through power generations, power converters, transmissions, and energy storages.

Photovoltaic (PV) system is one of the most mature RESs power generation technologies in the world, which is also the geographically most distributed measures of electricity production worldwide. It makes full use of solar radiation energy with the advantages of modularization, scalability in the generation and simple installation. Besides, the solar radiation as clean, renewable energy, it produces no pollution and never run out, hence achieved the policy support. A photovoltaic cell firstly developed in Bell Laboratories, America. Until now, Japan and Germany have mastered the most advanced PV system technology in the world. And China has occupied the largest installed and total solar power capacity globally [1].

In the condition that PV arrays as the main electrical sources for supply power, it is worth mentioning that the inverter control strategy can support reactive power when a low voltage fault occurs in AC bus without additional compensation device. Therefore, this paper introduced the PV system in four parts. 1) the detailed and accurate modeling of PV arrays; 2) acquiring output characteristics of PV array, P-V and V-I parameters are included; 3) The typical dual loop control and the improved reactive power and voltage (Q/V) control for three-phase grid-connected inverter; 4) conclusions and discussions of simulation results.

2 Modeling of PV Array

A PV cell, or solar cell, is the most basic electrical unit that converts solar radiation into electrical energy. In normal conditions, multiple cells that connected in series or/and parallel constitute a module or panel, which played the role of protecting semiconductor wafer in cells with tempered glasses, encapsulant and so on [2]. In order to generate cumulative voltage or/and current, a PV array implemented by strings of panels that connected in parallel at the same time, with each string consists of modules connected in series.

2.1. Solar Cell Model

The equivalent circuit of a general PV cell is shown in Fig. 1. The practical PV module includes $R_p$, the parasitic parallel (shunt) resistance and $R_s$, the series resistance. $R_s$ mainly due to the device itself that related with the semiconductor layer, while $R_p$ is based on the leakage current of the p-n junction [3], [4].

Generally, series part offers very little resistance, and shunt resistance being very high. According to modeling requirements, the output current could be chosen either in practical PV model (which refer to $I$, as shown in Fig. 1) or in the ideal condition ($I_{p,v,ideal}$) to represent the terminal...
output of one PV module that depends on designers.

Practical photovoltaic model

\[
I = I_{ph} - I_s \left( e^{\frac{V+IR}{N_sN_p}} - 1 \right)
\]

Where \(I_{ph}\) is the light-generated current (or photocurrent) that describes relations between photocurrent and irradiations, temperature; \(I_s\) is the diode saturation current (or the cell saturation of dark current); \(q\) is an electron charge (1.602×10^{-19} C); \(k\) is the Boltzmann constant (1.3807×10^{-23} J/K); \(T\) is the working temperature of cell, \(A\) is an ideal factor (generally between 1 and 1.5, and mainly dependent on PV manufacture technology).

The light-generated current is mostly influenced by both solar radiations and working temperature, which is given as follows [4], [5]:

\[
I_{ph} = \frac{G_{ref}}{G} \left( I_{ph,ref} + C_r (T - T_{ref}) \right)
\]

Where \(I_{ph,ref}\) is the light-generated current under standard conditions, generally refer to the external temperature at 25°C and irradiations is 1000W/m². In some cases, \(I_{ph,ref}\) can be replaced by short-circuit current \(I_{SC}\) under standard conditions, which can be obtained from production datasheet [5]. \(G\) (W/m²) is the irradiation on the device surface, and \(G_{ref}\) the solar radiation at the reference condition (1000W/m²). \(T\) and \(T_{ref}\) (K) are the actual and reference temperatures respectively. \(C_r\) (A/K) is the manufacturer supplied temperature coefficient.

However, sometimes when \(R_s\) is high enough and \(R_p\) is very low, then cell model can be considered as an ideal device, then equation (1) can be rewritten as [5]:

\[
I_{pv,ideal} = I_{ph} - I_s e^{\frac{V}{N_sN_p}} - 1
\]

2.2 PV Array Model

To provide greater power, a PV array consists of a set of modules that are electrically connected in series or/and parallel circuit. This is the typical configuration for a PV array model to provide the required current and voltage. If cells that connected in arrays have the same characteristic parameters. Therefore, the equivalent circuit of the PV array that corresponds with the solar cell is shown in Fig. 2.
From the P-V characteristic curves showing in Fig. 3, when irradiation is 1000W/m², the output power of the PV cells at the MPP (maximum power point) is around double the output power at MPP when G = 500W/m² (1000.6W output power at the MPP of a PV module when G=1000W/m² and the maximum power of 489.45W when G=500W/m²). And the voltages of MPP in both conditions are same (both 39.98V at MPP). For the I-V curve shown in Fig. 3, both MPPs with different irradiations that share the same voltage, which is also 39.98V, where the currents of both conditions are 25.02A and 12.24A respectively.

3 The Dual-loop Control for Providing Reactive power

Normally, the PV system running under unit power factor, but it is worth mentioning that control strategy can support reactive power when a low voltage fault occurs in AC bus without additional compensation device. The structure of PV system with three-phase voltage source inverter is presented in 3.1, which connected with an ideal three-phase voltage source. In 3.2, the typical dual-loop control for three-phase inverter I introduced. The proposed Q/V control strategy is expounded in 3.3. Finally, simulation results are discussed.

3.1 Three-phase Inverter Structure.

Transformation processes of PV arrays are mainly depending on the operations of grid-connected power converters and related components. The grid-connected inverter is the key component to convert DC voltage into the required AC voltage for supporting utility grid or loads. As shown in Fig. 4, a single-stage topology for PV system with a typical structure of three-phase grid-connected power inverter system is displayed where the filter capacitor placed in parallel with inverter and PV array.

\[
\frac{dI_{abc}}{dt} = V_{abc} - V_{fabc} \\
= V_{abc} - (V_{abc} + RI_{abc})
\]

\[
C \frac{dV_{fabc}}{dt} = I_{fabc} - I_{abc}
\]
3.2 The Typical Dual-loop Decoupling Control for Three-phase PV Grid-connected Inverter

Fig. 5 gives a typical dual-loop control topology of three-phase grid-connected inverter. The entire control processes can be divided into: 1) parameters measurements from grid and transformation of coordinates processes; 2) phase locked loop (PLL) control; 3) outer-loop control or primary control; 4) inner-loop control and 5) phase width modulation (PWM) technologies.

Overall, in order to acquire certain output power by the control methods, firstly the system parameters should be measured for calculations such as active (P\text{grid}) and reactive (Q\text{grid}) power. And then measured powers and reference values are sent to outer-loop controller to generate reference current signals, which as reference signals for inner-loop control. The inner-loop controller aims to provide SPWW modulator with control signals, which reduces the burden on system regulator, increases system response speed and system dynamic performance.

\begin{align*}
\begin{cases}
    P_{\text{grid}} &= \frac{3}{2} u_d i_d \\
    Q_{\text{grid}} &= \frac{-3}{2} u_d i_q
\end{cases}
\end{align*}

In this condition, active power only has relation with \(u_d\), and reactive power only controlled by \(u_q\). This is one type of the constant power control that under simplified mode.

3.2.1 Out-loop Controller

For variable control purpose, different control strategies are employed in the outer-loop controller. Generally, in the PV system, trying to provide maximum output power, and working at unit power factor. Control process for active power is given in Fig.6. And \(i_{q\text{ref}}\) is set to 0 directly for the unit power factor.

\begin{equation}
\begin{align*}
    u_d &= \left( K_p + \frac{K_i}{s} \right) (i_{d\text{ref}} - i_d) - \omega L i_q + u_d \\
    u_q &= \left( K_p + \frac{K_i}{s} \right) (i_{q\text{ref}} - i_q) + \omega L i_d + u_q
\end{align*}
\end{equation}

The feed-forward decoupling control and coupling compensation can realize independent control of dq components. The diagram of the inner-loop current controller is shown in Fig.7.

3.3 Reactive power/Voltage Control in PV System.

Sometimes PV arrays are required to provided certain reactive power for voltage fluctuation or faults, and improve low-voltage ride through capability (LVRT) \([7]\). A reactive control topology is employed to provide certain output reactive power. Due to the P-V parameters that displayed in Fig.3, a strategy by means of controlling output PV array voltage (V\text{dc}, shown in Fig. 5) to regulate output power (P) is introduced. The maximum power point tracking (MPPT) algorithm is used to find operation voltage V\text{mppt} for PV arrays that corresponds with the maximum output power. And then control V\text{mppt} as the reference signal, which can be shown in Fig.8, to regulate V\text{dc} as well as P \([8]\). The generated signal \(i_{d\text{ref}}\) is also sent...
to inner-loop controller to regulate P. Reactive power (Q) can also be controlled by PI controller where the \(i_{q_{ref}}\) is sent to inner-loop controller. While the inner control is as same as the typical dual-loop control method.

![Diagram](image)

**Fig. 8.** Typical Q/V Control.

### 4 Simulation Results

For the simulation model of the system, the resistance for per phase in the balanced lines is 0.0001 \(\Omega\), inductance value is 125 \(\mu H\). The rms (root mean square) value of phase to phase voltage for the main grid is 230 V.

In case 1, for the nominal condition of PV arrays, setting \(i_{q_{ref}} = 0\), which means running at unity power factor. While in case 2, based on the decoupling control and Q/V control strategy, active power is still required, additional reactive power is expected. According to (9), setting \(Q_{ref}=28.8\) kVar. The active power of PV arrays still output the maximum values under its external conditions. Besides, in order to test the dynamic working conditions of the PV system, in the both cases, solar irradiation changed from 1000 W/m² to 500 W/m² at 1 second.

According to the simulation structure, the output active power and reactive power in grid side under both control topology are measured for testing, which are given in Fig. 9.

![Curves of P and Q in different control conditions](image)

**Fig. 9.** Curves of P and Q in different control conditions.

- In both cases, at 1 second, the output power deduces half from 17.97 kW to 8.95 kW when irradiation changed from 1000 W/m² to 500 W/m², which shows quite perfect dynamic performance of active power control of PV arrays.
- In case 1, when setting \(i_{q_{ref}} = 0\), it can directly control output zero reactive power, which realizes working in unity power factor.
- Compared with simulation results in case 1 and case 2, since the reactive power control, blue lines (reactive power) changed, but red lines (active power) still maintained maximum output power under the control order. Thus, it verified the effectiveness and accuracy of decoupling control.
- In case 2, it is shown that the reactive power supporting in Fig. 9(b), the \(i_{q_{ref}} = -1.2\), according to (9), and the base value of Q is 16 kVar, as a result, the calculated value of Q in grid side is given.

\[
Q_{grid} = \frac{3}{2}u_{d}i_{q} = \frac{3}{2} \times 1 \times (-1.2) \times 16 = 28.8 \text{ kVar}
\]

- The curves of active power (P, red line) in case 1 and case 2 are almost same, which verified the strategy is feasible that regulate P by means of controlling V.

### 5 Conclusions

The simulation results show that the output active power is quite perfect even in case of irradiation changes. On the other hands, reactive power is required in many conditions and for the enhancements of low-voltage ride through capability. The proposed reactive power control method that based on the decoupling dual-loop control strategy can provide certain reactive power effectively. Simulation results verify the effectiveness and accuracy of the Q/V control.

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