Study on model current predictive control method of PV grid-connected inverters systems with voltage sag

N Jin, F Yang, S Y Shang, T Tao, J S Liu

1College of Electric and Information Engineering, Zhengzhou University of Light Industry, Zhengzhou 450000, China
2Pingdingshan Industrial College of Technology, Pingdingshan 476001, China
3State Grid Xuchang power supply company, Xuchang 461000, China
4Suoling Electric Co., Ltd, Zhengzhou 450000, China

E-mail: 1050048189@qq.com

Abstract. According to the limitations of the LVRT technology of traditional photovoltaic inverter existed, this paper proposes a low voltage ride through (LVRT) control method based on model current predictive control (MCPC). This method can effectively improve the photovoltaic inverter output characteristics and response speed. The MCPC method of photovoltaic grid-connected inverter designed, the sum of the absolute value of the predictive current and the given current error is adopted as the cost function with the model predictive control method. According to the MCPC, the optimal space voltage vector is selected. Photovoltaic inverter has achieved automatically switches of priority active or reactive power control of two control modes according to the different operating states, which effectively improve the inverter capability of LVRT. The simulation and experimental results proves that the proposed method is correct and effective.

1. Introduction

With the capacity and scale of PV generator continues to expand, grid-connected technology has become the research the focal point [1]. Under the condition of large scale new energy power station grid-connected, all the countries in the world provide the terms of the LVRT, which can make PV power station connected with network quickly or resume supply rapidly during grid faults [2, 3]. When the traditional double closed-loop vector control strategy is used [4], the control circuit contains multiple PI controllers, therefore, it is difficult to adjust the control parameters of PI in practical engineering. the PR current controller[5] is only used to control the fundamental frequency, but it is not clear how it will control to reactive power. Reactive power is injected into the grid through Static Var Compensator when a fault occurs in power system in literature [6], but SVC can't provide enough reactive power and bad dynamic performance. Solution of the LVRT through based on energy storage devices is proposed in reference [7], this approach can sufficiently solve the problem of power fluctuation, but the cost is too expensive.

5 Address for correspondence: F Yang, College of Electric and Information Engineering, Zhengzhou University of Light Industry, Zhengzhou 450000, China. Email: 1050048189@qq.com.
This paper comprehensively and deeply studies the single stage PV grid-connected inverter control system, and the method of MCPC with voltage sag is advanced. According to the grid voltage drop, the reactive current should be injected for reasonable compensation, and to ensure that the inverter can continue to maintain the grid. According to the current predictive model to predictive direct the active current id and reactive current iq, the optimal space voltage vector is selected by minimizing the cost function. In addition, the control method avoids the traditional control method of the external reactive power compensator and current controller with different frequencies, so it reduces the system cost and apply the inverter capability of LVRT which is easy to implement.

2. Another section of your paper

LVRT refers to the power grid malfunction or disturbance may lead to voltage sag of power access point. PV power system keep connected with the grid even in the situation of voltage sag within a certain rang and the prescribed time[8].

In 2011, State Grid Corp promulgated the technical regulation for PV power station access to power grid[9]. It is pointed out that the large and medium-sized PV power stations should have a certain LVRT capability and provide dynamic reactive power support during the process of LVRT. LVRT requirement is shown in Figure 1. If line voltage is above the limit curve, The PV power station should be connected with network; or it will be separated from the grid.

![Figure 1. LVRT requirements of the large and medium-sized PV power stations](image)

The German Grid Code has also provided for the relationship between the reactive current and the voltage drop depth[10], as shown in Figure 2. The reactive current to support the grid is not required when the voltage fluctuations in the range of -10% ~ +10%; The corresponding reactive current should be supplied 20% of the rated current in 10% the voltage sag; A 100% reactive current must be supplied if the voltage drop is up to 50%; Even after the voltage drop returns to the over 50%, the voltage support must be maintained.

![Figure 2. Reactive current relationship with voltage drop](image)
3. Low voltage ride through control technology

3.1. The current predictive mathematical model

Figure 3 displays a Three-phase Single Stage Grid-connected inverter, which is connected to main power system by using a line resistance R and a filtering inductance L. As reported by Kirchhoff law, the equations (1) of state under three-phase stationary frame is obtained as follows.

\[
L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R & -\omega L & 0 \\ \omega L & R & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} u_{aN} \\ u_{bN} \\ u_{cN} \end{bmatrix}
\]  

(1)

where \(e_a, e_b, e_c\) are three-phase grid voltage, \(i_a, i_b, i_c\) are grid-connected inverter output current, \(u_{aN}, u_{bN}, u_{cN}\) are output voltage of the inverter.

As reported by Park transformation, equations (2) can be rewritten in dq-frame

\[
L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} R & -\omega L & 0 \\ \omega L & R & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}
\]

(2)

where \(e_d, e_q, i_d, i_q\) are \(d, q\) components of the grid-connected voltage and current under \(dq\)-reference frame, \(u_d, u_q\) are \(d, q\) components of the inverter output voltage under \(dq\)-reference frame.

The three-phase single stage grid-connected PV inverter that switches status \(S_i (i=a, b, c)\) is defined as follows:

\[
S_i = \begin{cases} 
1 & \text{Turn-on of the up bridge arm, turn-off of the down bridge arm} \\
0 & \text{Turn-off of the up bridge arm, turn-on of the down bridge arm} 
\end{cases}
\]

(3)

In the model of three-phase grid-connected PV inverter shown in Figure 3, which existence seven various voltage vectors. The generated voltage space vectors is displayed in Figure 4.
The output voltage of the grid connected inverter is \( U_{i=d,q} \)

\[
\begin{bmatrix}
u_d \\ u_q
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix} 1 & -1/2 & -1/2 \\ \sqrt{3}/2 & \sqrt{3}/2 & 0
\end{bmatrix} \begin{bmatrix} S_d U_{dc} \\ S_q U_{dc} \\ S_u U_{dc}
\end{bmatrix}
\]

(4)

where \( U_{dc} \) is the voltage of DC bus, \( \theta \) is the space angle of power grid.

In the light of the resistance \( R \) is very small, the effect of \( R \) could be overlooked. After discretization, equations (2) can be written as

\[
\begin{bmatrix} i_d(k+1) \\ i_q(k+1)
\end{bmatrix} = \frac{T}{L} \begin{bmatrix} u_d(k) + \omega L i_d(k) - e_d \\ u_q(k) - \omega L i_q(k) - e_q
\end{bmatrix} + \begin{bmatrix} i_d(k) \\ i_q(k)
\end{bmatrix}
\]

(5)

The formula (5) is the predictive function based on model current prediction control.

3.2. Model current predictive control principle

PV inverter control structure[11-13] is shown in Figure 5. The optimum space voltage vector minimizing the cost function will be applied to the following sampling period. Thus the voltage vector corresponding to the switching state \( S_a, S_b \) and \( S_c \) are acquired by switching state optimization, in order to control switching of switch tube.

So as to select the optimal voltage vector, a cost function \( g \) has been set up. The predicted all current values will be compared through the cost function. To choose the minimum value function of voltage vector will be applied at the next moment. The value of error absolute sum between the predictive current and the reference current is used as the cost function:

\[
g(i) = |i_d^* - i_d(k+1)| + |i_q^* - i_q(k+1)|
\]

(6)

where \( i_d^* \) and \( i_q^* \) are reference values of the active and reactive current.

![Figure 5. Control diagram of photovoltaic inverter](image)

4. Low voltage ride through control strategy

The LVRT technology based on grid connected current control should supply reactive current to the grid according to the depth of the voltage drop, in order to support the grid voltage and recover power network[14].

When no fault occurs in the power grid, Priority must be given to meeting the active current. The output reference voltage \( U_{dc,ref} \) by maximum power point tracking (MPPT) technology for PV power generation. The error signal between the DC side voltage \( U_{dc} \) and the reference voltage \( U_{dc,ref} \) is the
input of proportional-integral (PI) regulator adjustment to $i^*_d$, then a reactive current reference value is given by the user directly. When the fault occurs, the inverter uses reactive priority control.

In the reactive priority control, the reference value of reactive current can be got with the voltage drop range between 10% and 50%:

$$i^*_q = 2\frac{U-U_N}{U_N} I_N = 2\frac{\Delta U}{U_N} I_N$$  

(7)

When the voltage drop is more than 50%, the reference value of the reactive current can be expressed as

$$i^*_q = -I_N$$  

(8)

In fact, considering the 1.1 times overload capability of the inverter itself[15], which allows the maximum continuous output current of the inverter to be $1.1i_N$. The active current of the inverter output is shown in the formula(9), where $i_N$ is the rated current of the power grid.

$$i^*_a \leq \sqrt{(1.1i_N)^2 - (i^*_q)^2}$$  

(9)

The three-phase output voltage and current of the inverter do the abc/dq rotation transformation by the synchronous rotation angle. The instruction current is responsible for the voltage sag detection, reference active and reactive current calculation. In normal conditions, the value of error absolute sum between the predictive current and the reference current is used as the cost function, thus the link of switch state optimization control switch tube conduction and shut off. When the power grid voltage sags, the reactive power priority control limits the active current to ensure the voltage recovery of generate reactive power by the inverter.

LVRT control flow chart of PV grid connected power generation system is shown in Figure 6, where $S(n)$ is the target switch state. $m, i$ are the variable Parameters. $i$ correspond to respective eight voltage vectors of inverter output from 0 to 7. $g_i$ is the value of evaluation function in the ith switch state.
5. Simulation results
The simulation model of PV system is designed as illustrated in Figure 3 by MATLAB/simulink, the purpose is researching characteristics of three-phase symmetrical faults. The simulation waveforms of the different situation are compared and analyzed on the following.

5.1. Comparative analysis before & after LVRT control input
Three phase symmetrical faults occurs in photovoltaic grid connected generation system at 0.08 s, the grid voltage drops to 0.6 p.u, then the fault is cleared at 0.14 s. The specific parameters are shown in Table 1.

| Parameters                        | Value   |
|-----------------------------------|---------|
| DC source voltage Udc             | 350V    |
| Grid line voltage e               | 110 V   |
| Filter inductance L               | 20mH    |
| Grid frequency f                  | 50Hz    |
| Power grid sag mode               | Symmetrical sag |
| Duration of voltage sag           | 0.06s   |

Table1. The simulation of system parameters.
As is evident from (a) of Figure 7, the output current of inverter remains stable under LVRT control during the fault period. The grid connected generation system should be injected into the power system after the voltage drop occurred by taking the reactive priority control, then the phase difference between the voltage and current is changed significantly. Figure 7 (b) and 7 (c) showed that the active power of the inverter output decreases during the voltage sag, the output reactive power increases during the voltage sag after the LVRT control strategy adopted. At this point PV power plant can provide priority a certain reactive power and become the reactive-load compensation equipment. After the voltage is restored to normal, active and reactive power can be quickly recovered to the steady state value before fault.

5.2. Comparative analysis with the traditional controller

In this section, the model predictive current control is compared with the traditional PI controller in system responsiveness. At 0.08s the active reference value is changed, which of the simulation results as shown in Figure 8. Where $I_{d1}$ is the output current of the inverter active component under the PI control. $I_{d2}$ is the output current of the inverter active component under the current predictive control. $I_{dref}$ is the reference current value.

Figure 8. Comparison of outputs when the reference instructions changed
The simulation results show that the current predictive control and PI control was changed in accordance with the current dynamic directives in the dynamic changes of reference current value. However, the response speed of the current predictive control is faster than the PI controller. The responses of model predictive current control is affected by sampling frequency and common mode voltage; with overshoot by PI control needs to set PI parameters, which will increase its control complexity and compute sharply.

5.3. Comparative analysis of different drop depth

Power grid voltage drop 0.02 P.U at 0.04s; drop 0.4 P.U at 0.08s; drop 0.7 P.U at 0.012s, the fault is cleared at 0.16 s.

![Figure 9. Comparison of outputs when depth of grid voltage sags changed](image)

It can be seen from Figure 9 that the PV power system must provide reactive current during voltage sag, the reactive current of the linear output when the voltage drop depth is 0.4p.u; When the voltage sag depth is 0.7p.u, and thus offer 100% reactive current. It shows that the reactive current output of the inverter can be changed according to the curve law shown in Figure 2.

6. Experiment

6.1. Experiment platform

To verify what be proposed control algorithm feasibility and effectiveness further, a three phase grid connected experimental platform based on PE-PRO is built as shown in Figure10. The control system is realized by the TMS320F28335 control chip of TI company, power device IGBT is 7MBP50RJ120, test instrument is DLM4000 YOKOGAWA series Mixed-signal oscilloscopes, APL-II DC power supply and so on.
6.2. Experiment result

Three phase AC voltage balance drops 60%, the experimental by using MCDPC plus compensation as displayed in Figure 11. The results is that the power $p = 1.1kW$ jump into $p = 0.5kW$, $q = 0$ jump into $q = 0.58kW$. A phase grid voltage and current would be phase-shifted, which can achieve the reactive power compensation of the inverter during the voltage sag, and maintain the voltage stability of the network.

![Figure 10. Experimental setup](image)

![Figure 11. Experimental waveforms](image)

(a) Voltage and current waveform  (b) power waveform

7. Conclusion

By using the model current predictive control method, the output voltage can be controlled under balanced conditions. When the control strategy is improved, using good dynamic response of MCPC strategy may quickly realize the control of grid connected inverter. Three phase symmetrical fault simulation examples are carried out on MATLAB/simulink, and the precision of the model is analyzed. This control strategy is utilized to regulate reactive power output in real-time, according to the grid voltage drop depth; and to improve the voltage of PCC; to support the continuous operation of PV power generation system; to help the rapid recovery of power grid.

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