Finite control set model predictive control of quasi-z-source inverter photovoltaic grid-connected

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Abstract. The PI control of the traditional quasi-Z inverter(qZSI) has difficulty in parameter correction and the shortcomings of hysteresis, while the traditional model predictive control (MPC) has a slower response and less precision for current control. In this paper, the current is transformed to the d-q coordinate system, and a suitable output vector is selected according to the limited switch state, which can track the reference current and perform finite set model predictive control (FCS-MPC). Compared with the traditional predictive control method, the current distortion rate is reduced, so that the photovoltaic inverter has a better output result.

1. Introduction

Photovoltaic is an important direction of new energy. The grid-connected photovoltaic inverter is the core part of realizing light energy utilization, which determines whether the photovoltaic system can operate stably [1], and the appropriate structure is also very important. Based on the traditional two-level inverter, the quasi-Z source structure can realize the control of the DC side voltage boost and buck, and has the advantages of low distortion rate and high system reliability. It is widely used in the system [2,3]. However, under the actual application background, the efficiency of photovoltaic power generation is easily affected by changes in the external environment, and the stability is not high enough, which will affect the safety of grid connection. Based on the original structure, adding an MPPT system after the inverter can adjust the power change of the load, which can effectively improve the power fluctuation problem in the inverter [4], and the output voltage of photovoltaic cells needs to be adjusted to stabilize.

Literature [5] uses the PI control method for grid-connected inverter, but qZSI needs to control multiple targets. The traditional PI control has weak control ability for multi-variable targets. Most control methods also have the problem of time lag and are limited. The ensemble model predictive control can make up for these shortcomings and can improve the dynamic effect capability of the target. In this paper, qZSI is used as the control target, and the FCS-MPC control strategy is studied. The optimal control state is determined through the objective function. After simulation verification, the system control result has good dynamic performance and stable performance, and the current harmonic distortion rate is also Lower [6]. After the inverter meets the requirements, it will not affect the power quality after being connected to the grid. Therefore, the control link is a very important link in the use of new energy. Finite set model predictive control can improve the responsiveness of the inverter system. This article applies it to the quasi-Z-source photovoltaic grid-connected system. Simulation verification proves its effectiveness and feasibility.
2. The structure of the qZSI

2.1. Topology

The quasi-Z-source photovoltaic inverter has a photovoltaic power generation array that can output DC voltage after control and a qZSI structure that can boost voltage. Its main structure is shown in Figure 1. \( L_1 \) and \( L_2 \) are energy storage inductors, and \( C_3 \) is the filter capacitor on the photovoltaic output side. \( C_2 \) and \( C_3 \) are energy storage capacitors, \( D_m \) is a diode, used to reverse cut off the current. On the right is the grid side, \( L_g \) and \( R \) is the filter inductor and equivalent resistance. Because of the special structure of qZSI, boost control can be achieved.

![Fig.1 Structure diagram of qZSI](image)

The difference between the quasi-Z-source inverter and the traditional inverter is that there is a through state (\( ST \)). In order to prevent the \( ST \), the traditional voltage source inverter needs to add a dead time, and qZSI can use the characteristics of \( ST \) and Non-\( ST \) to save energy. The inductors and capacitors are charged to realize the step-up and step-down control of the inverter voltage. The \( ST \) and Non-\( ST \) are shown in Figure 2.

![Fig.2 Non-\( ST \) and \( ST \) of qZSI](image)

In the Non-\( ST \), as shown above Fig.2 (a), the diode undergoes forward voltage conduction. Currently, the photovoltaic cell and the inductor simultaneously charge the capacitor and transfer the current to the grid side. The capacitor absorbs energy and the inductor releases energy. Currently, the switch state is valid or zero vector. According to Kirchhoff's law, there is equation (1).

\[
\begin{align*}
\text{eq1} & : u_{i1} = u_{pc} - u_{c1} & u_{i2} &= -u_{c2} & u_{dc} &= u_{c1} + u_{c2} \\
\text{eq2} & : i_{i1} = i_{c1} - i_{dc} & i_{c2} &= i_{c1} - i_{dc} & i_{dca} &= i_{i1} + i_{i2} - i_{dc}
\end{align*}
\]

In the \( ST \), the diode bears the reverse voltage and cuts off the current. Currently, the photovoltaic cell and the charged capacitor simultaneously charge the inductor, the capacitor releases power, and the inductor absorbs energy. As shown on equation (2).

\[
\begin{align*}
\text{eq3} & : u_{i1} = u_{pc} + u_{c2} & u_{i2} &= u_{c1} & u_{dca} &= u_{c1} + u_{c2} \\
\text{eq4} & : i_{i1} = -i_{c2} & i_{c2} &= -i_{i1} & i_{dc} &= i_{i1} + i_{i2}
\end{align*}
\]
Therefore, the steady-state values of capacitor voltage and inductor current are respectively Equation (3). By adjusting the duty cycle D, the DC output voltage can be adjusted to improve power utilization.

\[
\begin{align*}
U_{c1} &= \frac{1-D}{1-2D} U_p, U_{c2} = \frac{D}{1-2D} U_p \\
I_{L1} &= \frac{1-D}{1-2D} I_{dc}, I_{L2} = \frac{1-D}{1-2D} I_{dc}
\end{align*}
\] (3)

2.2. Mathematical model of qZSI

Because of the two working states of qZSI: Non-ST and ST, according to the equivalent circuit diagrams of Fig. 2 and Fig. 3, the switching function \( S \) has three states,

\[
S_x = \begin{cases} 
\text{Non-ST} & \quad 1, S_{a1}, S_{b1}, S_{c1} = 1, S_{a2}, S_{b2}, S_{c2} = 0 \\
0 & \quad S_{a1}, S_{b1}, S_{c1} = 0, S_{a2}, S_{b2}, S_{c2} = 1 \\
ST & \quad S_{a1}, S_{b1}, S_{c1}, S_{a2}, S_{b2}, S_{c2} = 1 
\end{cases}
\] (4)

The zero vector includes three states \((0,0,0)\) and \((1,1,1)\), since the output is the same, only one \((1,1,1)\) is used here to indicate the \( ST \), Table. 1 show all the switch state combinations of the output voltage vector under two levels.

| Switch states | Non-ST | ST |
|---------------|--------|----|
| output | \( u_0 \) | \( u_1 \) | \( u_2 \) | \( u_3 \) | \( u_4 \) | \( u_5 \) | \( u_6 \) | \( u_7 \) | \( u_g \) |
| \( S_{a1} \) | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| \( S_{a2} \) | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| \( S_{b1} \) | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| \( S_{b2} \) | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| \( S_{c1} \) | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| \( S_{c2} \) | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |

There are two states: through and non-through, so the output of the inductor voltage of qZSI can be expressed as equation (5).

\[
L_1 \frac{di_{L1}}{dt} = u_{c2} + u_{pv} \\
L_1 \frac{di_{L2}}{dt} = u_{pv} - u_{c1}
\] (5)

Use the forward Euler difference to differentiate the above equation (5), and obtain the state quantity at time \( k \) of the mathematical equation (6) under the discretization. Both are the sampling input at the current time, \( i_{L1}(k+1) \) and \( i_{L2}(k+1) \) is the predicted current value at the next moment.

\[
\begin{align*}
\dot{u}_{i_{L1}}(k+1) &= \dot{i}_{i_{L1}}(k) + \frac{T_s}{L_1} \left[ u_{c2}(k) + u_{pv}(k) \right] \\
\dot{u}_{i_{L2}}(k+1) &= \dot{i}_{i_{L2}}(k) + \frac{T_s}{L_1} \left[ u_{pv}(k) - u_{c1}(k) \right]
\end{align*}
\] (6)

Model the inverter grid-connected module and convert it to the \( d-q \) coordinate system. It is possible to go to equation (7), where \( u_{d}, u_{q} \), \( i_{d}, i_{q} \) are the output voltage and current of the inverter respectively, and \( e_{d}, e_{q} \) are the grid side respectively the components in the \( d-q \) coordinate system.
After differential discretization of the above equation, the equation (8) can be obtained, where \( i_d(k+1), i_d(k+1) \) are the predicted values of the \( d-q \) axis current at the next moment, \( i_d(k), i_q(k) \) respectively. \( i_d(k), i_q(k) \) is the \( d-q \) axis current value at the current moment, and \( u_d(k) \) and \( u_q(k) \) are the \( d-q \) axis voltage values at the current moment.

\[
\frac{di_d}{dt} = \frac{1}{L_g} (u_d - e_d - Ri_d)
\]
\[
\frac{di_q}{dt} = \frac{1}{L_g} (u_q - e_q - Ri_q)
\]

\( \text{(7)} \)

\[
i_d(k+1) = (1 - \frac{RT_d}{L_g})i_d(k) + \frac{T_d}{L_g} (u_d(k) - e_d(k))
\]
\[
i_q(k+1) = (1 - \frac{RT_q}{L_g})i_q(k) + \frac{T_q}{L_g} (u_q(k) - e_q(k))
\]

\( \text{(8)} \)

3. finite set model predictive control of qZSI

3.1. FCS-MPC principle of current

The principle of finite set model predictive control is to first establish a predictive model based on the mathematical model of the object, and then obtain the predicted value of each vector output of the controlled object in different switching states, establish the corresponding cost function, and select the smallest cost function. The switching state is then output to the photovoltaic inverter. Compared with other control methods, no PWM modulation is required, and it is easy to implement and has better flexibility. The specific principle is shown in Fig.3 [7].

3.2. FCS-MPC of qZSI

The FCS-MPC control structure of qZSI photovoltaic grid-connected inverter system is shown in the Fig 4, which mainly includes (max power point track) MPPT control of the photovoltaic array, as well as direct and non-direct judgment control, DC side voltage loop control and inner loop current control, predicted switch judgment output module.
The switching state of qZSI is shown in the table I. The two-level inverter structure has 8 vectors (including 6 effective vectors and 2 zero vectors). qZSI requires a through state boost, so only one set of zero vectors is applied to achieve ST.

The predictive mathematical model of the inverter side of the grid under the \( d-q \) axis is formula (8), and the predictive model of the impedance source network capacitor voltage and inductor current is equation (9).

\[
ST: \\
\begin{align*}
    i_{L1}(k+1) &= i_{L1}(k) + \frac{T}{L_{L1}}(u_{in}(k) + u_{C2}(k)) \\
u_{C1}(k+1) &= u_{C1}(k) - \frac{T}{C}i_{L1}(k)
\end{align*}
\]

\[
Non-ST: \\
\begin{align*}
    i_{L1}(k+1) &= i_{L1}(k) + \frac{T}{L_{L1}}(u_{in}(k) - u_{C1}(k)) \\
u_{C1}(k+1) &= u_{C1}(k) + \frac{T}{C}[i_{L1}(k) - (S_{aC}i_a + S_{bC}i_b + S_{cC}i_c)]
\end{align*}
\]

3.3. Cost Function

In order to achieve multi-objective control, capacitor voltage and inductor current need to be added to the calculation of the cost function. At the same time, in order to control the grid-connected current, a current term needs to be added to the cost function. \( \lambda_L \) and \( \lambda_C \) are the weight coefficients of the inductor current and the capacitor voltage, so the cost function is equation (11):

\[
g = \left| i_{L1}^*(k) - i_{L1}(k+1) \right| + \left| i_{L2}^*(k) - i_{L2}(k+1) \right| + \lambda_L \left| i_{L1}^*(k) - i_{L1}(k+1) \right| + \lambda_C \left| u_{C1}^*(k) - u_{C1}(k+1) \right|
\]
4. Simulation Study

In order to verify the feasibility and effectiveness of the FCS-MPC control method of qZSI, a simulation model of the photovoltaic grid-connected system and control algorithm is established. The specific parameters are shown in Table 2, and the sampling period $T_s=20 \mu s$.

| Parameters     | Value     |
|----------------|-----------|
| Grid Voltage   | 380       |
| Inductance L1=L2 | 1mH     |
| Capacitance C1=C2 | 1000 \(\mu\)F |
| Resistance R   | 0.8 \(\Omega\) |

Set $0.3s < t^* < 0.6$ as $i^* = 20A$, $i^* L1 = 25A$, $0.3 < t^* < 0.6$ as $i^* = 28.5A$, $i^* L1 = 33.5A$, The simulation result is shown in Fig.6.
Fig. 6 Simulation result

Fig. 6. (a) is Voltage value of capacitor C1, the (b) is current value on the grid side, the (c) is the current value of L1, the (d) is THD changes, the (e) is DC side voltage value.

It can be seen from (a) that when the reference power changes in 0.3 seconds, the capacitor voltage value can be restored to a stable value after a small overshoot. The adjustment process is relatively fast, that is, the system can quickly go from a state to another state and the dynamic performance is better. The (b) shows that the grid-connected current responds quickly, the distortion is relatively low, and the state adjustment is relatively fast. The (c) shows that the inductor current of the qZSI network can quickly track the reference value, and the switch between the through state and the non-through state is faster. In (d), the conversion of THD meets the requirements of power quality. The (e) is the DC side voltage value, which is rectangular wave shape, because each cycle includes the boost state of the qZSI structure, and the ST and Non-ST switches required.

5. Conclusion

qZSI can boost the DC voltage of the photovoltaic output by switching between the ST and Non-ST switch states, and without adding dead time, using FCS-MPC, by establishing a cost function, eliminating parameter selection and PWM modulation. The through state is determined by prediction, which reduces the difficulty of control and improves the response speed of photovoltaic grid-connected. It can change rapidly according to the reference value, and the state is excessively fast. From the simulation results, the dynamic response and steady-state performance of the grid-connected
system are good, and the inverter result is that the THD remains low, which meets the needs of the photovoltaic power generation system to be integrated into the grid.

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