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Fault Tolerant Control of Grid Connected Inverters Based on Low-Voltage Ride Through

Zaisheng Wang [1, *], Shiya Zhao [2], Yang Li [1], Fang Yang [3], Zhan Zhao [3]

[1] State Grid Henan Electric Power Company Luoyang Power Supply Company, Luoyang, China
[2] State Grid Henan Electric Power Company Yichuan Power Supply Company, Yichuan, China
[3] State Grid Henan Electric Power Company Nanyang Power Supply Company, Nanyang, China
* Corresponding Author: Zaisheng Wang

ABSTRACT

To enhance the reliability of new energy grid connected systems, a fault-tolerant model predictive control strategy with low-voltage ride-through capability for grid connected inverter bridge arms has been proposed. Firstly, the operational principles following a single-phase bridge arm fault in the grid-tied inverter are analyzed. Then, a fault-tolerant structure for the grid connected inverter is established by creating a virtual bridge arm using direct current-side capacitors. Subsequently, a current prediction model is established, and control is implemented using redundant vectors. Additionally, by dynamically adjusting reactive current compensation commands based on the relationship between grid voltage drops and reactive current commands, the system is ensured to maintain continuous and stable operation even during grid voltage fluctuations. Finally, experimental results demonstrate that this fault-tolerant control strategy can still maintain the continuous and stable operation of the system when bridge arm faults occur due to grid voltage drops at the inverter grid connection point.

KEYWORDS

Fault-tolerant; Low-voltage-ride-through; Model Predictive Control; Grid Connected Inverter; Reactive Compensation.

1. INTRODUCTION

In recent years, with the rapid development of new energy generation technologies such as photovoltaic and wind power, the integration technology of new energy and grid has attracted much attention [1-2]. However, new energy grid-connected inverters cannot operate normally due to high-frequency switching which may lead to problems such as loss of drive signals and damage of switching components. In addition, when the grid voltage drops, the traditional grid-connected control strategy is difficult to actively provide reactive power support to the grid, which may lead to problems such as current overload and repeated connections and disconnections, further reducing the reliability of the new energy grid-connected system.

To ensure that the new energy grid-connected system can continue fault-tolerant operation after the inverter bridge arm failure, literature [3-4] proposes a three-phase four-bridge-arm inverter topology for zero-sequence voltage reduction. Although this scheme can efficiently realize fault-tolerant control, the topology design adds a set of bridge arms, which will increase the upfront cost. In addition, in order to avoid the unlisting phenomenon when the grid voltage drops, literature [5] investigates the low voltage ride-through control strategy for wind power grid-connected systems. Literature [6], on the other hand, coped with the voltage collapse problem under weak grid and proposed a dual-mode switching control strategy for inverter Low voltage ride-through (LVRT), which effectively mitigated the system destabilization problem under weak grid. However, none of the above literatures considered the possible adverse effects of a weak grid on the inverter.

To address the problem of abnormal operation of the grid-connected system after bridge arm failure caused by grid voltage dips, the inverter is controlled from two perspectives, namely, inverter fault-tolerant control and LVRT, in order to enhance the system reliability. A fault-tolerant structure applicable to the grid-connected inverter is designed, and the relationship between the voltage vector and the faulty bridge arm is analyzed to maintain the stable operation of the grid-connected system by using the remaining bridge arm and the corresponding voltage vector. In addition, a low-voltage ride-through control model is developed, and the reactive current compensation signals under different grid voltage drop depths are calculated to provide reactive power support for the grid.

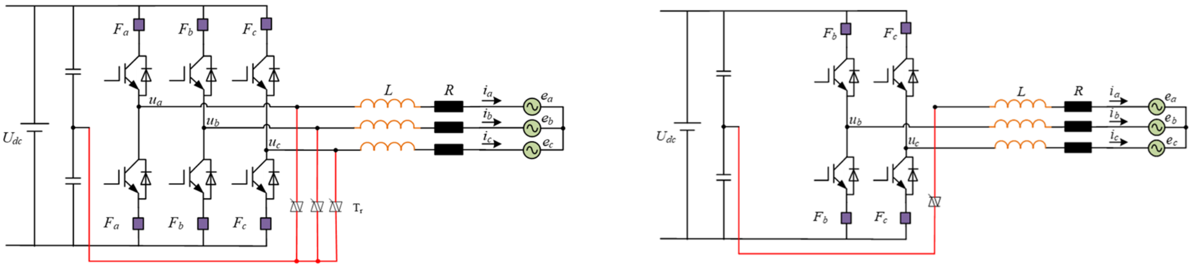
2. CURRENT PREDICTIVE CONTROL MODEL BASED ON FAULT-TOLERANT CONTROL AND LOW VOLTAGE RIDE-THROUGH

2.1. Fault-Tolerant Control Model

The fault-tolerant structure of the grid-connected inverter is shown in Fig. 1(a), when a fault occurs in one phase of the bridge arm of the inverter, the bridge arm of the faulty phase is fused by a fast fuse, and at the same time, the bidirectional thyristor of the corresponding phase is conducted, so that the faulty-phase output of the inverter is directly connected to the midpoint of the capacitor of the dc side, which constitutes the fault-tolerant control structure, as shown in Fig. 1(b), and the vector diagrams of voltages before and after the faults are shown in Fig. 2 [7]~[9]. Establishing the voltage equation under the dq coordinate system for the inverter system leads to equation (1).

$$\boldsymbol{u}_{\mathrm{dq}} = L\frac{d\boldsymbol{i}_{\mathrm{dq}}}{dt} + R\boldsymbol{i}_{\mathrm{dq}} + \boldsymbol{e}_{\mathrm{dq}} \tag{1}$$

where $\boldsymbol{i}_{\mathrm{dq}}$ is the grid-connected current; $\boldsymbol{u}_{\mathrm{dq}}$ is the output voltage; $\boldsymbol{e}_{\mathrm{dq}}$ is the grid voltage; L is the filter inductance; R is the parasitic resistance; T is the sampling period.



(a) Normal State

(b) A-Phase Bridge Arm Fault Condition

Figure 1. Fault Tolerant Structure of Grid Connected Inverter

Discrete equation (1) yields the predicted current as in equation (2).

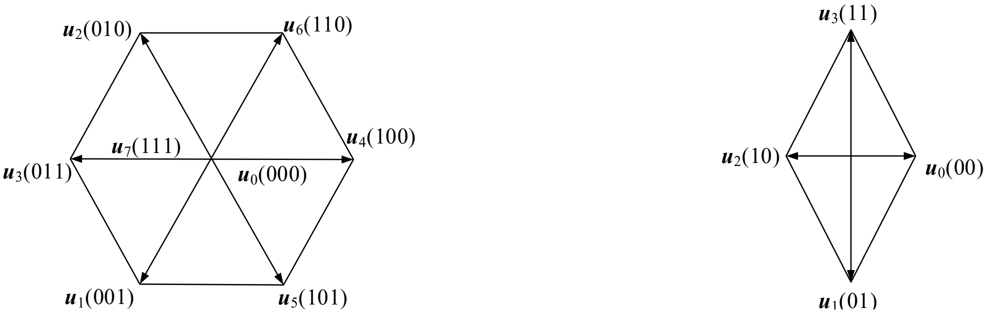
$$\boldsymbol{i}_{\mathrm{dq}}(k+1) = (1+\frac{RT}{L})\boldsymbol{i}_{\mathrm{dq}}(k) + \frac{T}{L}[\boldsymbol{u}_{\mathrm{dq}}(k)\text{-}\boldsymbol{e}_{\mathrm{dq}}(k)] \tag{2}$$

where $\boldsymbol{X}(k)$ is the value of variable $\boldsymbol{X}$ at moment k.

The fault tolerant inverter has only 4 switching devices. Analyzing the relationship between the output voltage vector of the fault tolerant inverter and the switching states leads to (3).

$$\boldsymbol{u}_{abc}=\frac{U_{dc}}{3}\begin{bmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{bmatrix}\begin{bmatrix}0.5\\ S_b\\ S_c\end{bmatrix} \tag{3}$$

where S_b, S_c are the BC phase switching state values, 1 for the upper bridge arm conduction and 0 for the lower bridge arm conduction.



(a) Normal State (b) A-Phase Bridge Arm Fault Condition

Figure 2. Voltage Vectors of Grid Connected Inverter

The voltage vectors of the inverter after the A-phase bridge arm failure are Clrake transformed to obtain the voltage vector table shown in Table 1.

Table 1. Voltage Vector During A-Phase Bridge Arm Fault

Voltage Vector	A Phase Voltage u_a	B Phase Voltage u_b
(0 0)	$U_{dc}/3$	0
(0 1)	0	$-U_{dc}/\sqrt{3}$
(1 0)	0	$U_{dc}/3$
(1 1)	$-U_{dc}/\sqrt{3}$	0

2.2. Low Voltage Ride-Through Mode

During operation, the grid-connected system may not be able to maintain normal operation due to grid faults, and even repeated grid connections and disconnections may occur, resulting in greater grid fluctuations and faults [10]~[11]. Therefore, when designing a grid-connected system, it becomes very important to endow the system with sufficient LVRT capability to cope with this situation.

When a dip in grid voltage occurs, the grid-connected system needs to support the recovery of grid voltage by delivering reactive power. As shown in Fig. 3, the grid-connected system needs to inject the maximum reactive current into the grid when the range of grid voltage dips is between 0 and 50%; while the required reactive current decreases with the increase of the depth of grid dips when the range of grid voltage dips is between 50% and 90%; and the system does not need to inject reactive currents into the grid when the range of grid voltage dips is between 90% ~00% as shown in Eq. (4).

$$\begin{cases} i_{\mathrm{qr}}=I_{\mathrm{N}} & ,\ e_{\mathrm{d}}/e_{\mathrm{N}}\le 0.5\\ i_{\mathrm{qr}}=\left(2-2E/E_{\mathrm{N}}\right)\times I_{\mathrm{N}} & ,\ 0.5<e_{\mathrm{d}}/e_{\mathrm{N}}\le 0.9\\ i_{\mathrm{qr}}=0 & ,\ e_{\mathrm{d}}/e_{\mathrm{N}}>0.9 \end{cases} \tag{4}$$

where i_{qr} is the reactive current to be compensated by the inverter; I_N is the rated grid-connected current; e_d is the actual grid voltage; e_N is the rated grid voltage.

Considering that the grid-connected system has an overload capacity of 1.1 times, i.e., the maximum operating current is 1.1 times the rated grid-connected current IN, the active current i_{dr} of the inverter can be when the grid voltage dips:

$$i_{dr} = \sqrt{(1.1I_N)^2 - i_{qr}^2} \tag{5}$$

where i_{dr} is the active current of the inverter.

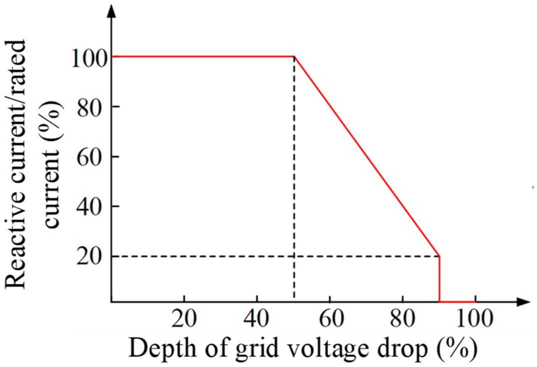


Figure 3. Relationship between the depth of grid voltage drop and the required reactive current compensation

2.3. Predictive Control Strategy Based on Fault-Tolerant Control And Low-Voltage Ride-Through

When the grid voltage fluctuates between 0.9 p.u. and 1.1 p.u., the grid can be considered to be at normal operating level. When the grid voltage falls below 0.9 p.u., the low voltage ride-through control algorithm is activated. The core of this algorithm is to determine the optimal voltage vector based on the error between the predicted and compensated currents, which is given in the following equation:

$$g = | i_d(k+1) - i_{dr} | + | i_q(k+1) - i_{qr} | \tag{6}$$

The predicted currents calculated from all the voltage vectors in Fig. 2 are sequentially brought into the cost function, and the voltage vector corresponding to the minimum value of the cost function is applied to the next cycle.

In practice, when a fault occurs in the bridge arm of phase A, the bridge arm of the faulty phase is fused by a fast fuse, and at the same time, the bidirectional thyristor of the corresponding phase is energized, so that the output of the faulty phase of the inverter is directly connected to the midpoint of the capacitor of the dc-side, constituting a fault-tolerant control structure, and then the voltage vectors are calculated according to Table 1. Next, the grid voltage, grid current and inverter output voltage are Park transformed to the dq coordinate system, and then the reactive and active currents to be compensated are calculated according to the LVRT model. Meanwhile, the predicted reactive and active currents are calculated according to the current prediction model. Finally, the predicted currents are substituted into the cost function and the voltage vector that minimizes the cost function is selected as the optimal vector and applied in the next cycle.

3. SIMULATION VERIFICATION

The proposed control strategy is validated based on the MATLAB/Simulink platform with the following parameters: dc voltage 400V, rated grid phase voltage V (e_N=134.72A), rated grid-connected phase current A (i_{dN}=24.5A, i_{qN}=0A), grid frequency 50Hz, sampling frequency 10kHz, and filtering inductance 20mH.

In order to verify the effectiveness of the proposed control strategy, the simulation is carried out to verify the A-phase bridge arm after a fault. Fig. 4 demonstrates the three-phase currents under normal state and fault-tolerant control, and the simulation results show that the THD of the grid-connected current is 3.46% under normal state and 4.55% under fault-tolerant control, and the sinusoidal degree of the three-phase currents is good, which meets the requirements for grid connection.

In Fig. 5, the current tracking situation when the grid voltage fluctuates and dips to different degrees is shown. According to the results in the figure, under normal voltage fluctuation, there is no need to activate the LVRT function, the active current maintains the rated operating current, and the current THD is 4.55%. When the grid voltage drops to 0.8 p.u., the LVRT function is activated, the current THD is 4.95%, and the grid-connected system is overloaded and operates with a reactive current of about 10 A and an active current of about 25.1 A. When the grid voltage drops to 0.4 p.u., the current THD is 4.35%, the reactive current is about 24.5 A, and the active current is about 11.2 A. Therefore, when the grid voltage drops , the strategy is able to ensure stable operation.

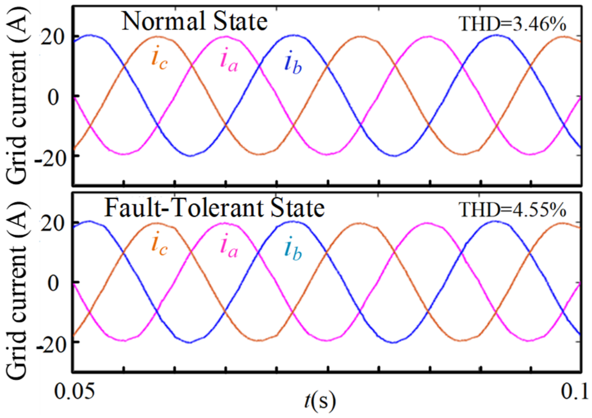


Figure 4. Grid connected current under fault-tolerant control

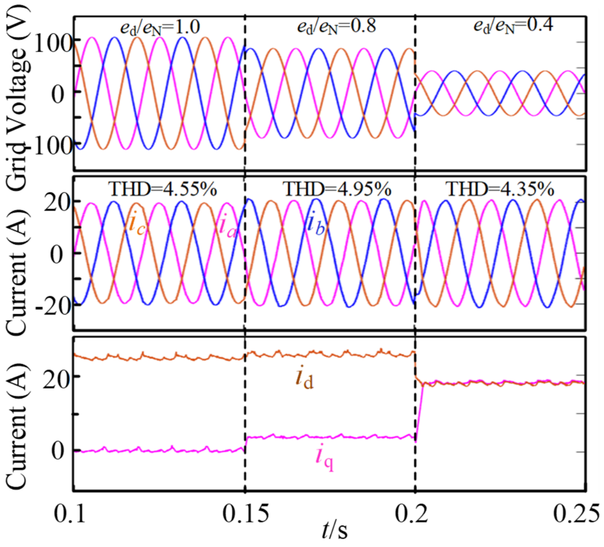


Figure 5. Grid connected current during voltage drop in the power grid

References are cited in the text just by square brackets [1]. (If square brackets are not available, slashes may be used instead, e.g. /2/.) Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under the heading *References*, see our example below.

4. SUMMARY

In this paper, a methodology to enhance the reliability of the grid-connected system is proposed, which takes into account bridge arm failures under low-voltage ride-through conditions and by reconfiguring the inverter into a fault-tolerant control structure after a bridge arm failure occurs. Subsequently, the LVRT control model is developed based on the grid voltage dips as well as the required reactive current compensation, and the reactive current is adjusted to meet the required reactive power support of the grid. Experimental results show that this control method can operate continuously and effectively provide the required reactive power support of the grid even when grid voltage drops and bridge arm faults occur.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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