Fault Tolerant Three Level ANPC Inverter Circuit with Finite Set Model Predictive Control

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Abstract. An improved active neutral point clamped (ANPC) inverter circuit topology is proposed. Through the fault-tolerant leg, the fault-tolerant performance of the inverter circuit has been greatly improved. The fault-tolerant leg works as an actuating device which control the neutral point to remain stable, when there is no fault with the inverter. When some power tubes are broken the leg works as the redundant device to replace the power tubes. The finite set model predictive control method is used for this inverter circuit. This control method is quite suitable for the electronic circuit. This method is employed to lower THD and to advance its dynamic, so that the error tolerance and high power output of the aviation inverter are satisfied. The feasibility and effectiveness are proved by simulations.

1. Introduction
The power supply needed in the aircraft is often inconsistent with the main power supply, and there is no special AC power supply in some aircraft's DC power supply systems, but its electronic devices such as radar, gyroscope and radio navigation equipment require the alternating current of 36V or 115V of the frequency 400Hz. At the same time, in order to satisfy the emergency power supply for the flight instrument and the related equipment, the inverter circuit must be connected with the battery as the emergency power supply to convert the DC power into alternating current when the main power supply is broken. In order to satisfy the reliability of the aircraft power supply, the inverter circuit needs a higher fault tolerance. The design of its fault tolerant topology not only takes into account the increase of the failure probability caused by the increase of power devices, the multiplied increase in the complexity of the control methods, and the increase of the cost of the circuit.

A four-leg fault-tolerant NPC inverter was introduced in [1], and in some document the output of the fault phase is directly connected with the DC bus neutral point through an additional device or a the fourth leg. In document [2] the fourth leg is added to the inverter, but this topology can not afford the fault situation that simultaneous breakage of two phase. Considering these methods and the fault situation of aeronautical inverter, we put forward a new topology based on the document.

The development of control theory has gone through the two stages of classical control theory and modern control theory. With the continuous development of material science and semiconductor technology, the topology of inverter circuit is becoming more and more complex. The types of control methods based on inverter circuit are more and more, and the characteristics of the mathematical model and control method can be obtained. It is divided into linear control and nonlinear control. the linear control is PID, and the nonlinear control conclude repetitive control [3], hysteresis Control[4], deadbeat control, Finite Control Set Model Predictive Control(FCS—MPC)[5-7].
The FCS-MPC can make full use of the discrete properties of power electronic circuits, through the FCS-MPC each possible combination of switch states are considered, and the switch state, which minimized objective function was used as circuit control, the complex mixed integer quadratic programming problem can be avoided.

2. The topology analysis of the fault tolerant ANPC inverter

In this paper, the traditional ANPC inverter circuit is improved by redundancy thought, and its topology is shown in Figure 1.

From the topology of figure 1, it can be seen that the fault tolerant ANPC inverter circuit structure has a redundant leg comparing to the original ANPC inverter. On the right side of the topology, it can be seen that the three phase leg is the same as the original ANPC inverter circuit, and the middle point of each phase is connected with the redundant leg. The point NP on the left side of the redundant leg is the neutral point of the all circuit and the VNP is the virtual point. Through the transformation between the NP and the VNP corresponding control signal and the fault isolation means, the circuit can realize the fault-tolerant function.

When the circuit works normally, the redundant leg acts as a device for adjusting the location in the circuit. The capacitor $C_o$ is charged to $V_{dc}/2$ before the operation of the circuit. At this time, the voltage is maintained by the virtual neutral point VNP. The $\Delta U$ and $\Delta I$ are defined as (1).

$$\Delta U = V_{dc}/2 - U_{C_o} ; \Delta I = i_{s_a} + i_{s_b} + i_{s_c}$$  \hspace{1cm} (1)

In formula (1), $i_{s_a}, i_{s_b}, i_{s_c}$ are the current which flow from the virtual neutral point VNP to the midpoint of two clamp power pipes in the three-phase bridge arm of A, B and C, and the current from point VNP into the direction of the three phase bridge arm is positive. When the circuit works normally, the switch tube $S_5$ and $S_6$ have been turned off.

In the situation of $\Delta U < 0, \Delta I < 0, U_{C_o} > V_{dc}/2$, the switch $S_1$ and $S_3$ are engaged, the capacitor is in the discharge state, and the capacitor voltage drops. When $U_{VNP} = V_{dc} - U_{C_o}$ The voltage of the neutral point will gradually rise to $V_{dc}/2$. 

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In the situation of $\Delta U < 0, \Delta I > 0, U_{C_o} > V_{dc}/2$, the switch $S_2$ and $S_4$ are engaged, the capacitor is in the discharge state, and the capacitor voltage drops. When $U_{VNP} = V_{dc} - U_{C_o}$, the voltage of the neutral point will gradually drop to $V_{dc}/2$.

In the situation of $\Delta U > 0, \Delta I < 0, U_{C_o} < V_{dc}/2$, the switch $S_2$ and $S_4$ are engaged, the capacitor is in the charge state, and the capacitor voltage rises. When $U_{VNP} = V_{dc} - U_{C_o}$, the voltage of the neutral point will gradually drop to $V_{dc}/2$.

In the situation of $\Delta U > 0, \Delta I > 0, U_{C_o} < V_{dc}/2$, the switch $S_1$ and $S_3$ are engaged, the capacitor is in the charge state, and the capacitor voltage rises. When $U_{VNP} = V_{dc} - U_{C_o}$, the voltage of the neutral point will gradually rise to $V_{dc}/2$.

By comparing the magnitude of current and capacitor voltage, the switches in redundant leg are switched back and forth between $S_1$, $S_3$ switch state and $S_2$ and $S_4$ switch state. The advantage of this method is that it does not need to balance the relationship between the output performance and the offset of the loci by calculating the control amount of the algorithm, and it is easy to realize, but the disadvantage is obvious. This method is used to control the middle loci, which requires high switching frequency and large switching loss.

When the circuit works normally, the right three phase APNC output circuit is the same as the traditional ANPC operation mode. The switch states of one phrase of inverter is shown in Table 1, similarly to the rest two phrases, when “1” represents “on”, “0” represents “off”.

| Switch state | $S_{a1}$ | $S_{a2}$ | $S_{a3}$ | $S_{a4}$ | $S_{a5}$ | $S_{a6}$ | Output voltage |
|--------------|----------|----------|----------|----------|----------|----------|----------------|
| P            | 1        | 1        | 0        | 0        | 0        | 1        | $V_{dc}/2$     |
| OU1          | 0        | 1        | 0        | 0        | 1        | 0        | 0              |
| OU2          | 0        | 1        | 0        | 1        | 1        | 0        | 0              |
| OL1          | 0        | 0        | 1        | 0        | 0        | 1        | 0              |
| OL2          | 1        | 0        | 1        | 0        | 0        | 1        | 0              |
| N            | 0        | 0        | 1        | 1        | 1        | 0        | $-V_{dc}/2$    |

When the power transistor fails, the topology of the circuit topology is reconstructed, taking the A phase fault as an example. When the A phase leg power tube $S_{a1}$ break down, the A phase can not output P state and OL2 state in the circuit output state shown in Table 1. Because the OL2 state output level is 0, the other redundant 0 level state can be supplemented, but the P state output voltage is $V_{dc}/2$, so the circuit must be fault-tolerant to guarantee the circuit work normally. The fault-tolerant scheme is shown in figure 2, it shows the current path in different states. The phrase A is linked to VNP by $G_{avn}$, The phrase B, C are linked to NP by $G_{bn}$ and $G_{cn}$.
Figure 2. The fault-tolerant scheme of $S_{a1}$ break down when $S_{a2}$ break down, phrase A cannot output P state and OU1 and OU2 state. Its circuit topology reconfiguration scheme is shown in figure 3.
The situation of $S_{a3}$, $S_{a4}$ break down are similar to the situation of $S_{a1}$, $S_{a2}$ break down, so there is no longer to give unnecessary details.

When the same side power pipe fault between the different phase leg. For example, $S_{a2}$ in A and $S_{b2}$ in B break down at the same time, the failure can not output P state and OU1, OU2 state, in which OU1 and OU2 can be replaced by other redundant 0 level state. We will mainly introduces how to output P state. The topology is shown in figure 4.

3. The FCS-MPC of ANPC inverter
Define the switch variables $S_a$, $S_b$ and $S_c$ to represent the output state of each phase leg. Take the A phase as an example, $S_a=1$ represents the A phrase output P state; $S_a=0$ represents the O state of the A phrase (OU1, OU2, OL1, OL2 are all belong to O state); $S_a=-1$ represents the output of P state, Thus there comes to 27 state form table 1 and figure 1, and the vector shows in figure 5. The expression of
voltage between the output of each leg and the virtual neutral point $U_{AN}$ can be obtained as the expression (2)

$$u_{AN} = \frac{V_d}{2} \times S_a$$

The voltage between the A, B and C of the three-phase and the point ‘O’ of the capacitance in the capacitor can be known from the topology are expression (3)

$$u_{AO} = u_{AN} - u_{ON}; u_{BO} = u_{BN} - u_{ON}; u_{CO} = u_{CN} - u_{ON} = \frac{1}{3}(u_{AN} + u_{BN} + u_{CN})$$

The $u_{ON}$ is the voltage between O and VNP. Combining (2) and (3), there comes out expression (4)

$$\begin{bmatrix} u_{AO} \\ u_{BO} \\ u_{CO} \end{bmatrix} = \frac{V_d}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

Defining space variables $\alpha = e^{(2\pi/3)}$, there comes to $u_o$

$$u_o = \frac{2}{3}(u_{AO} + au_{BO} + \alpha^2 u_{CO})$$

Similarly, the three-phase inductor current, capacitor voltage, output current, can be transformed into space vector form (6)

$$i_f = \frac{2}{3}(i_{af} + \alpha i_{bf} + \alpha^2 i_{cf}); u_c = \frac{2}{3}(u_{c_a} + au_{c_b} + \alpha^2 u_{c_c}); i_o' = \frac{2}{3}(i_{o_a'} + \alpha i_{o_b'} + \alpha^2 i_{o_c'})$$

According to Kirchhoff’s voltage and current law and the working principle of inductance and capacitance, the formula (7) is available.

$$\begin{cases} \frac{dx}{dt} = Ax + Bu_o + B_o i_o' \\ y = Cx \end{cases}$$

Where $x = \begin{bmatrix} i_f \\ u_c \end{bmatrix}$; $A = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{L} & 0 \end{bmatrix}$; $B_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$; $B_2 = \begin{bmatrix} 0 \\ -\frac{1}{C} \end{bmatrix}$; $C = \begin{bmatrix} 0 & 1 \end{bmatrix}$

The mathematical model shown in formula (7) is a continuous mathematical model. In the finite set model predictive control, the continuous mathematical model needs discretization like (8).
\[
\begin{align*}
x(k+1) &= A^* x(k) + B_1^T u_\alpha(k) + B_2^T i_{p}(k) \\
y(k) &= C x(k)
\end{align*}
\] (8)

Where \( A^* = e^{AT} \), \( B_1^* = \int_0^T e^{At} B_1 \mathrm{d}t \), \( B_2^* = \int_0^T e^{At} B_2 \mathrm{d}t \), \( T_s \) is the sample time.

The reference voltage at the \( k+1 \) time \( u^{ref}(k+1) = 3u^{ref}_c(k-1) - 2u^{ref}_c(k-2) \)

In this paper, taking the output voltage optimization as an example, the selection of its objective function is described in (9).

\[
g = \left[ u^{ref}_c(k+1) - u_c(k+1) \right]^2 + \left[ u^{ref}_{cp}(k+1) - u_{cp}(k+1) \right]^2
\] (9)

\( u^{ref}_c(k+1) \) and \( u_c(k+1) \) are the real axis components of reference output voltage and predicted voltage at \( k+1 \) time respectively. \( u^{ref}_{cp}(k+1) \) and \( u_{cp}(k+1) \) are the imaginary axis components, respectively. The algorithm flow chart is shown in Figure 6.

![Algorithm flow chart](image)

According to the model of inverter circuit switching function constructed by formula (8), the predictive value \( u_c(k+1) \) can be calculated by the controlled amount under the action of 27 possible vectors at the time of \( K \) which is made of by all the \( u_{AN} \), \( u_{BN} \) and \( u_{CN} \). Combining the \( u_c(k+1) \), \( u^{ref}_c(k+1) \) and formula (8), the best switch state can be got which goes to the \( g_{min} \).

4 Simulation

According to the inverter topology shown in Figure 1, the strategy researched in this paper was proved by MATLAB/Simulink, main simulation parameters were provided as following. \( V_{dc} = 270V \), filter inductance \( L=2mH \), filter capacitance \( C=40\mu F \), rated frequency is 400Hz, sampling period \( T_s = 10\mu s \), The load is 80Ω.

The steady state experiment results of FCS-MPC based on the circuit were shown in Figure 7, THD=2.34%, which is easy for filter design. The transient experiment results are shown in Figure 8. The Figure 8 shows the change of load from empty to full load, and it shows that the FCS-MPC can meet the dynamic change requirements of the system. No matter the steady state or the transient state this method can make output has a good power quality, which meet the requirement of aeronautical inverter.
Figure 7. steady state experiment results

Figure 8. transient state experiment results

5. Conclusions
The tolerant three level ANPC inverter provide more fault tolerance function for the aeronautical inverter. The FSC-MPC make the low THD and fixed harmonic of output voltage are obtained, which was easy for filter design. Finally the steady state and transient properties of the strategy was proved by simulations.

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