A Novel Virtual Space Vector Modulation Scheme for Three-Level NPC Power Converter with Neutral-Point Voltage Balancing and Common-Mode Voltage Reduction for Electric Starter/Generator System in More-Electric-Aircraft

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Abstract—In recent years, More-Electric-Aircraft (MEA) becomes the state-of-the-art. One of the essential issue need to be solved is neutral-point (NP) voltage drift in three-level neutral-point-clamped (3L-NPC) power converter because of load power factor (PF) and high modulation index (MI) working condition. Meanwhile, since common-mode voltage (CMV) can damage the motor shaft, thereby degrading the efficiency and reliability of electric starter/generator (ESG) system. In this paper, a proposed modulation scheme is presented based on virtual-space vector concept to achieve both NP voltage balancing and lower CMV. Meanwhile, $g$-$h$ coordinate is used to overcome excessive computational burden which is common in high-frequency power converter applications. The results of simulation investigation show the effectiveness and significant improvement of proposed modulation strategy in ESG system.

Index Terms—Three-level NPC power converter, CMV reduction, $g$-$h$ frame, Electric starter/generator system, More-Electric-Aircraft, Neutral-point voltatge balancing, Virtual Space Vector PWM

I. INTRODUCTION

MEA has become a cutting-edge technology over the last few decades [1]–[4]. It aims at making more use of electrical power instead of pneumatic, hydraulic and mechanical power. One of essential parts in MEA is the ESG system which can be shown in Fig.1. In order to achieve high efficiency of fuel consumption in the aircraft, whole system is mainly made up of a permanent magnet synchronous machine (PMSM) and power converter. Because of lower voltage stress on power device, improved output-voltage quality and bidirectional energy path, 3L-NPC power converter, in Fig.2, is selected.

In the configuration of ESG, PMSM is mechanically connected with aircraft engine shaft, and is electrically connected with 3L-NPC power converter which is the key point between mechanical and electrical part. At the beginning, power converter runs as an inverter which can drive PMSM to crank engine compressor. At 10krpm, engine ignites at this moment. After that, ESG is in the standby mode. When the engine speed increases to 20krpm, the generation mode starts. In this mode, engine cranks the PMSM and make it as a generator. Meanwhile, 3L-NPC power converter works as a rectifier which transfers energy from AC-side to DC-link for supplying on-board loads.

Since 3L-NPC power converter is the interface of ESG system, its reliability and efficiency have an influence on its performance. One of the inherent challenge is the NP voltage unbalancing issue. The NP voltage drift causes extra over-
in calculation is needed to execute program in DSP. [15] has been used g-h frame to simplify dwell time expression. Hence, this modulation strategy is also based on this coordinate for this purpose.

The configuration of this paper is organized as follows. In Section II, NTV and NTV$^2$ are briefly reviewed. In addition, CMV of these two types of modulation schemes are analyzed, respectively. A novel NTV$^2$ with NP voltage balancing and CMV reduction is proposed in Section III. The simulation results are shown in Section IV and conclusions are drawn in Section V.

II. NTV AND NTV$^2$ SCHEME IN 3L-NPC POWER CONVERTER

A. NTV

The space vector diagram in Fig.3 shows 27 basic switching states of 3L-NPC power converter topology. Briefly, take Sector-I for example, when $V_{ref}$ is located in triangle 3, it can be composed by nearest three space vectors tagged with position 1, 2 and 3. The switching sequence is POO→PON→OON → ONN. By using voltage-second principle, the dwell time for each vector can be calculated as follow:

$$\begin{align*}
V_{ref} &= V_1d_1 + V_2d_2 + V_3d_3 \\
d_{s1} + d_{s2} + d_{s3} &= 1
\end{align*}$$

(1)

Similarly, nearest three space vectors tagged with position 1, 3 and 4 can synthesize $V_{ref}$ in triangle 5, corresponding switching sequence is POO→PON→PNN→ONN.

From (1), the duty cycle in different MI range can be calculated. The relationships of duty cycle between small vector and medium vector are attained in Fig.4. It can be seen that the duty cycle of small vector is decreased when increasing MI, which in turn can impact the control capability of NP voltage balancing.

When considering PF, It can be seen from Fig.5 that the NP voltage balancing capability is degraded at PF=± 90°. Since
low PF is worst characteristic for ESG system, NTV scheme can hardly be used in this application.

B. NTV

Space vector diagram of NTV is showed in Fig.6 and the definitions in Sector-I are listed as follows:

\[ V_{Z0} = V_{O(OOO)}(0) \]
\[ V_{ZL1} = V_{L1(PNN)}(0) \]
\[ V_{ZL2} = V_{L2(PPN)}(0) \]
\[ V_{ZS1} = \frac{1}{2} V_{S1(POO)}(-i_a) + \frac{1}{2} V_{S1(ONN)}(i_a) \]
\[ V_{ZS2} = \frac{1}{2} V_{S2(PPO)}(i_c) + \frac{1}{2} V_{S2(OWN)}(-i_c) \]
\[ V_{ZM1} = \frac{1}{3} V_{S1(ONN)}(i_a) + \frac{1}{3} V_{M1(PON)}(i_b) + \frac{1}{3} V_{S2(PPO)}(i_c) \]

From definition above, \( V_{ref} \) is composed with a series of space vectors that do not induce extra NP current during a switching cycle, thereby balancing NP voltage within all range of MI and PF. Assuming \( V_{ref} \) is located in triangle 4, the switching sequence is PPO→PPN→PON→PNN→ONN. Apparently, more switching actions are needed comparing with NTV scheme.

C. CMV Analysis for NTV and NTV Scheme

The CMV generated by power converter is defined by (2). \( V_{ao} \), \( V_{bo} \) and \( V_{co} \) are the phase voltage with respect to the NP potential, respectively.

\[ V_{com} = \frac{1}{3} (V_{ao} + V_{bo} + V_{co}) \]  (2)

Through the calculation, the corresponding CMV for basic switching states can be attained. CMV contains a series of DC voltage value which is the reason of bearing deterioration and winding failure.

| Type       | Switching States | \(|V_{com}|\) |
|------------|------------------|--------------|
| Zero Vectors | OOO              | 0            |
|             | PPN              | \( V_{dc}/2 \) |
| Small Vectors | POO OON OPO NOO OOP ONO | \( V_{dc}/6 \) |
|             | ONN PPO NON OPP NNO POP | \( V_{dc}/3 \) |
| Medium Vectors | PON OPN NPO NOP ONP PNO | 0           |
| Large Vectors  | PNN PPN NPN NPP NNP PNP | \( V_{dc}/6 \) |

III. A NOVEL MODULATION SCHEME FOR NP VOLTAGE BALANCING AND CMV REDUCTION IN ESG SYSTEM

Since trigonometric functions can be avoided during dwell time calculation and sector judgment can be easily achieved as well. Therefore, \( g-h \) frame is used in proposed modulation scheme according to (3).
Small vector NP balancing capability follows:

\[ V_{Z0} = V_{OOO}(0) \]
\[ V_{ZL1} = V_{PPN}(0) \]
\[ V_{ZL2} = V_{L22(PPN)}(0) \]
\[ V_{ZS1} = \frac{1}{2} V_{PPN}(0) + \frac{1}{2} V_{PNP}(0) \]
\[ V_{ZS2} = \frac{1}{2} V_{PNP}(0) + \frac{1}{2} V_{NPN}(0) \]
\[ V_{ZM1} = \frac{1}{3} V_{OPN}(ia) + \frac{1}{3} V_{PON}(ib) + \frac{1}{3} V_{PNO}(ic) \]

Thus, the effective virtual space vectors can be chose as follows:

- 1) choosing a series of virtual space vectors can produce average zero NP current during a switching cycle.
- 2) lower CMV can be achieved from these vectors.

Thus, the effective virtual space vectors can be chose as follows:

For NP voltage balancing and CMV reduction, the principle of switching-state selection should meet:

1) choosing a series of virtual space vectors can produce average zero NP current during a switching cycle.
2) lower CMV can be achieved from these vectors.

Thus, the effective virtual space vectors can be chose as follows:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
1 & -\frac{1}{\sqrt{3}} & \sqrt{\frac{2}{3}} \\
0 & \frac{2}{\sqrt{3}} & 0 \end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

\[
\begin{bmatrix}
V_g \\
V_h
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

\[
V_{ZL1} = V_{L22(PPN)}(0)
\]

Fig. 6. Space vector diagram with proposed NTV\(^2\) scheme

Fig. 7. Space vector diagram with proposed NTV\(^2\) scheme

IV. Simulation Results

The simulated ESG system given in Fig.9 is built in MATLAB/PLECS environment and its parameters are listed in Table.III. Initially, ESG system runs in the starter mode, and flux-weakening control is operated at roughly 0.45s. With the engine ignition, the speed of PMSM reaches to 20krpm. Then generation mode starts by connecting a 5kW resistive load to the DC-link at 1s and the droop conrol takes over DC-link voltage regulation at the same time. As shown in Fig.9, PMSM speed can describe ESG system status in every stage. In Fig.10, It can be seen that NP voltage is well balanced during the starter and generation mode.

The comparison of CMV with traditional NTV and improved NTV\(^2\) modulation scheme are respectively showed in Fig.11 and Fig.12, where less CMV within 1/6 of DC-link voltage can be achieved.
TABLE II
DWELL TIME OF SPACE VECTORS IN TRIANGLE 3,4&5 IN SECTOR-1

| Division | Space Vectors | Dwell Time |
|----------|---------------|------------|
| S1-3     | PNP           | (1-g-2h)Ts |
|          | PNO           | hTs        |
|          | PNN           | (2g+h-1)Ts |
|          | PON           | PPN         |
|          | OPN           | (1-g-2h)Ts |
|          | OPN           | (1-g-h)Ts  |
|          | PPN           | (2h+g-1)Ts |
| S1-4     | PNO           | (1-g-h)Ts  |
|          | PNN           | gTs         |
| S1-5     | PNO           | (1-g-h)Ts  |
|          | PNN           | (1-h-2g)Ts |
|          | PON           | gTs         |
|          | PPN           | (2h+g-1)Ts |
|          | OPN           | gTs         |
|          | NPN           | (1-h-2g)Ts |

V. CONCLUSIONS
In this paper, NP voltage balancing and CMV reduction are both achieved based on proposed modulation scheme for 3L-NPC power converter used in high-speed drive system. Through the analysis, it can be seen that NTV$^2$ have more advantages over NTV in high MI and low PF conditions, which...
is the worst working condition of ESG system. Secondly, CMV is reduced for the purpose of efficiency and reliability, which is beneficial to the high-speed drive system. Besides, the modulation scheme is based on g-h frame for simplifying calculation, thereby reducing computational burden in microcontroller. All of this can provide significant benefits for electric starter/generator system of MEA.

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