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 low 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 voltage 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 show 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.

Fig. 1. ESG system of more-electric-aircraft.

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-

Fig. 2. The topology of 3L-NPC power converter

stress on IGBT. Besides, it produces low-order harmonics in the AC-side. The problem has been studied by researchers for many years. Traditional method makes full use of small vector [5]. That is, for the sake of compensating NP current caused by medium vector, choosing nearest-three space vector (NTV) with redundant P- and N-type small vector. Or, according to NP unbalanced range, adding a feedback control loop to dynamically adjust duty cycle of each small vector. In contrast, authors firstly proposed the concept of nearest-three virtual space vector (NTV²) PWM to balance NP voltage [6]. Some modulation schemes based on NTV² are presented for different targets [7]–[9]. In [10], the authors proposed a modified SVPWM without using medium vector, it can solve the NP voltage drift in high-speed drive of ESG system. As high modulation index (MI) and low power factor (PF) are worst conditions for traditional NP-voltage balancing control algorithm [4]. This problem should be taken into account for optimal ESG system as well. Therefore, NTV² is the best option to be considered. On the other hand, CMV has detrimental effects on motor due to shaft current, ground leakage and electromagnetic interference noise. More precisely, voltage stress on motor caused by CMV could lead to premature failure of motor winding insulation. In [11], CMV reduction method is proposed with virtual space vector modulation, but it can be only employed in two-level inverter topology. Because medium space vector and zero-vector OOO both do not produce CMV in 3L-NPC power converter, reference voltage vector can be synthesized by these vectors to attain zero CMV [12]. Nevertheless, the restriction on MI make it hard to be applied in high DC voltage utilization application area. Especially, MI is about 0.98 during generation mode in ESG system. This problem has been solved in [13] with six virtual medium vectors. However, because of the influence of medium vector, the NP voltage oscillation is highly increased, which may damage DC-link capacitors. In [14], NP voltage and CMV reduction can be achieved through operating mode selection, but NP voltage drifts in high PF condition. The paper proposes a new approach for both CMV reduction and NP voltage balancing in all range of MI and PF. In addition, the fundamental frequency is 1kHz at 20krpm, high performance

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 NTV² are briefly reviewed. In addition, CMV of these two types of modulation schemes are analyzed, respectively. A novel NTV² 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 NTV² 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:

$$\begin{cases} V_{ref} = V_1 d_1 + V_2 d_2 + V_3 d_3 \\ d_{S1} + d_{S2} + d_{S3} = 1 \end{cases} \quad (1)$$

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.

Fig. 3. Space vector diagram of NTV modulation scheme

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 $PF = \pm 90^\circ$. Since

low PF is worst characteristic for ESG system, NTV scheme can hardly be used in this application.

B. NTV²

Space vector diagram of NTV² is showed in Fig.6 and the definitions in Sector-I are listed as follows:

$$V_{Z0} = V_{0(OOO)}(0)$$

$$V_{ZL1} = V_{L1(PNN)}(0)$$

$$V_{ZL2} = V_{L2(PPN)}(0)$$

$$V_{ZS1} = \frac{1}{2}V_{S1(POO)}(-i_a) + \frac{1}{2}V_{S1(ONN)}(i_a)$$

$$V_{ZS2} = \frac{1}{2}V_{S2(PPO)}(i_c) + \frac{1}{2}V_{S2(OON)}(-i_c)$$

$$V_{ZM1} = \frac{1}{3}V_{S1(ONN)}(i_a) + \frac{1}{3}V_{M1(PON)}(i_b) + \frac{1}{3}V_{S2(PPO)}(i_c)$$

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 NTV² 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.

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

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.

TABLE I
CMV ACCORDING FOR SWITCHING STATES

Type	Switching States	$ V_{com} $
Zero Vectors	OOO	0
	PPP NNN	$V_{dc}/2$
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).

Fig. 4. Polar plot of the duty cycle of small vector and medium vector with different MI

Fig. 5. Small vector NP voltage-balancing capability 3-D plot

Fig. 6. Space vector diagram with NTV² scheme

$$\begin{aligned} \begin{bmatrix} V_g \\ V_h \end{bmatrix} &= \begin{bmatrix} 1 & -\frac{1}{\sqrt{3}} \\ 0 & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \\ &= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \end{aligned} \quad (3)$$

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:

$$\begin{aligned} V_{Z0} &= V_{OOO}(0) \\ V_{ZL1} &= V_{PNN}(0) \\ V_{ZL2} &= V_{L2(PPN)}(0) \\ V_{ZS1} &= \frac{1}{2}V_{PPN}(0) + \frac{1}{2}V_{PNP}(0) \\ V_{ZS2} &= \frac{1}{2}V_{PNN}(0) + \frac{1}{2}V_{NPN}(0) \\ V_{ZM1} &= \frac{1}{3}V_{OPN}(i_a) + \frac{1}{3}V_{PON}(i_b) + \frac{1}{3}V_{PNO}(i_c) \end{aligned}$$

Fig.8. shows space vector diagram with corresponding co-ordinate. Note that V_g and V_h are both normalised with large vector value ($2V_{dc}/3$). For example, when V_{ref} is located in triangle 4, the half switching sequence during a period is $OPN \rightarrow PPN \rightarrow PON \rightarrow PNN \rightarrow PNO$, and the dwell time of each space vector for synthesizing can be showed in Table.I, where T_s is a switching period.

Fig. 7. Space vector diagram with proposed NTV² 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 control 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 NTV² modulation scheme are respectively showed in Fig.11 and Fig.12, where less CMV within 1/6 of DC-link voltage can be achieved.

Fig. 8. Space vector diagram with proposed NTV² scheme

TABLE II
DWELL TIME OF SPACE VECTORS IN TRIANGLE 3,4&5 IN SECTOR-1

Division	Space Vectors	Dwell Time
S1-3	PNP	$(1-g-2h)T_s$
	PNO	hT_s
	PNN	$(2g+h-1)T_s$
	PON	hT_s
	PPN	$(1-g-2h)T_s$
	OPN	hT_s
S1-4	OPN	$(1-g-h)T_s$
	PPN	$(2h+g-1)T_s$
	PON	$(1-g-h)T_s$
	PNN	$(2h+g-1)T_s$
	PNO	$(1-g-h)T_s$
S1-5	PNO	$(1-g-h)T_s$
	PPN	$(1-h-2g)T_s$
	PON	gT_s
	PPN	$(2h+g-1)T_s$
	OPN	gT_s
	NPN	$(1-h-2g)T_s$

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 NTV² have more advantages over NTV in high MI and low PF conditions, which

TABLE III
ESG SYSTEM PARAMETERS

Simulation Parameter	Value
$L_d=L_q$	99μH
Pole Pair	3
Switching Frequency	16kHz
PM Flux	0.03644V _s /rad
Base Speed	8000rpm
Capacitor Value($C_1=C_2$)	4500μF
DC-link Voltage	270V

Fig. 9. PMSM speed diagram in every stage

Fig. 10. Voltage of upper and lower side capacitor (C_1 & C_2)

Fig. 11. CMV with traditional NTV² scheme

Fig. 12. CMV with proposed modulation scheme

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 micro-controller. All of this can provide significant benefits for electric starter/generator system of MEA.

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