Observation of Neutral Point Ripple of a Three-Level NPC Inverter with SVPWM

Ahmetcan Akuz, *Member, IEEE,* and Ali Belli, *Member, IEEE*

***Abstract*— Three-Level Neutral-Point-Clamped (NPC) Inverter is used in many industrial applications due to its advantages in terms of harmonics content and achieved power level. However, the main concern in this topology is the neutral point (NP) voltage ripple. This paper investigates the neutral point voltage ripple of Three-Level NPC Inverter with Space Vector Pulse Width Modulation (SVPWM) under different load frequency conditions. The research made on MATLAB Simulink model. Simulink model includes SWPWM block, an Interior Permanent Magnet Synchronous Machine (IPMSM) as load and Field Oriented Control (FOC) block additional to the 3 Level NPC Inverter. In this research, the implementation of the SVPWM for a Three-Level NPC Inverter and comparison of the NP voltage ripple levels for different output frequencies are conducted. The comparison is made with four different IPMSM operation conditions and results are compared by checking the NP voltage and line-to-line phase voltage.**

***Index Terms*— Field oriented control (FOC), interior permanent magnet synchronous machine (IPMSM), neutral point (NP), NP voltage ripple, neutral point clamped (NPC), three-level NPC inverter space vector pulse width modulation (SVPWM).**

I. INTRODUCTION

MULTILEVEL inverters gained importance during the beginning of the two decades due to their advantages compared to the classical two level inverters. Multilevel inverters have multiple advantages, such as, low harmonics in output voltages and current, less switching power losses on the switches due to lower dv/dt, less voltage stress on semiconductor switches, and higher quality output waveform. Therefore, a new family of multilevel inverters has emerged as the solution for different applications, for example, large powerful engine drives, distribution systems, AC power supplies and medium voltage grid.

Variety of inverter topologies have been developed with the aim of reducing the total harmonic distortion (THD) and improving the efficiency. Neutral-point clamped (NPC) inverter, flying capacitor (FC) inverter, cascaded H-bridge (CHB) inverter, multilevel-based parallel inverters, split coupled inductor inverters (SCI) and U cells are the most known. Although, there are plenty of advantages of multilevel inverters, there are some limitations and drawbacks. The capacitor imbalance in NPC and FC topologies, large number of isolated power sources used in CHB topology and imbalance of common-mode current in SCI topology are the examples for limitations and drawbacks.

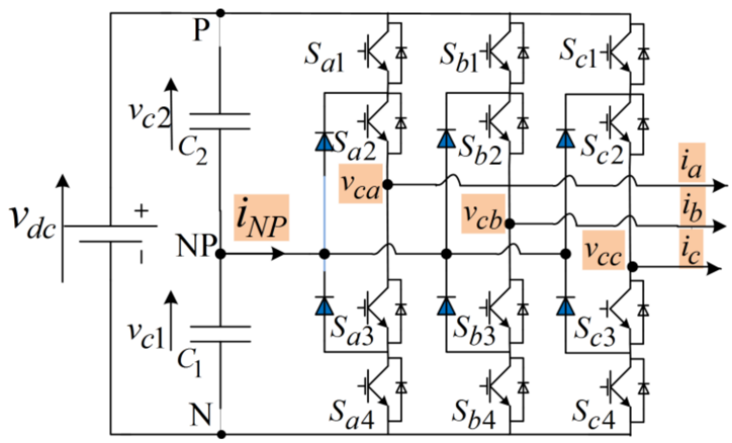

Fig. 1. Structure of a three-level NPC inverter

Subsequently, more interest will be given to the issue of neutral point (NP) voltage balance control in the NPC topology shown in Fig. 1. The unbalanced charging and discharging of the two DC-link capacitors cause NP voltage imbalance. The imbalance reflects as 3rd harmonic ripple at the NP. The harmonic content increase and risk on the switching devices due to the unequal voltage sharing among them causes detrimental effects because of the imbalance.

The NP voltage imbalance has been widely studied and various balancing control methods have been proposed. Although there are lots of successful and efficient control methods developed to reduce the neutral point voltage ripple and balance the voltage division, there is not any research on the natural behavior of the ripple by the change of the output load operation conditions.

In this article, an investigation on the neutral point voltage ripple variation under different load conditions is examined. The load is chosen as interior permanent magnet synchronous machine (IPMSM), which is popular to driven with three-level inverters. The ripple values are observed with different output torque and speed conditions of the IPMSM. In addition, the line-to-line voltage is also compared.

The rest of this article is organized as follows. The three-level space vector modulation and FOC is presented in Section II. Section III represents the IPMSM motor block. Section IV includes the simulation results and the comparison. Finally, there are the possible problems associated with NP voltage ripple, suggested approaches to limit the ripple and summary at Section V.

II. Generated SVPWM and FOC Simulation Blocks

A. Space Vector Pulse Width Modulation Method

Space Vector Pulse Width Modulation (SV-PWM) method is a widely used robust and efficient method for motor driving methods. In this method, the phase current of the motor is adjusted with respect to desired speed and torque. The I_d and I_q currents are calculated according to these values. With help of these values, V_d and V_q values are calculated, and reference vector can be found. Then they transformed from rotating frame to stationary frame to frame by using inverse Clarke and Park Transformation and switching states are adjusted until it reaches desired speed and torque values of motor by measuring phase current and position information of motor.

The states for 3-level inverter can be defined in three different levels, P, 0 and N. Terminal voltage levels for 3-level inverter are Vdc/2, 0, -Vdc/2 respectively. In each leg, P can be obtained by opening upper two stiches of one leg. If the two switches at the middle of the leg is open 0 state can be obtained. The other two switches at the bottom must be opened for N state of inverter [1]. The states can be seen in Table 1.

TABLE 1
Switching States of 3-Level Inverter

State	S1	S2	S2	S4	Terminal Voltage
P	1	1	0	0	Vdc/2
O	0	1	1	0	0
N	0	0	1	1	-Vdc/2

The control of motor can be done by finding exact voltage vector and its phase. All possible voltage vectors with respect to switching states can be seen in Fig. 2. To find exact position and degree of the vector, this diagram is divided to six different sectors with 60-degree differences.

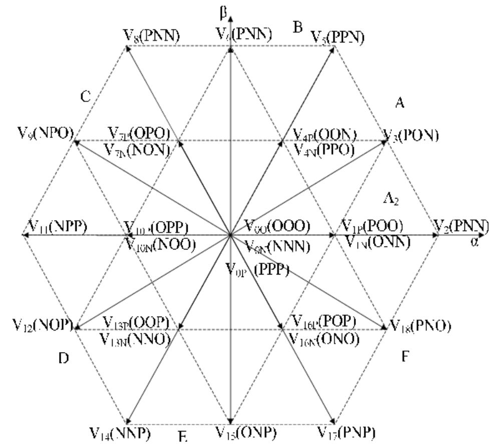

Fig. 2. Structure of a three-level NPC inverter

Magnitudes of these vectors are calculated by the states of each leg. These sectors also include four different regions. These regions are used to determine magnitude of the vector. Also, switching vectors are determined with these regions. For example, in Fig. 3, V_{ref} vector is in region 2. To obtain this vector, V1, V2 and V7 vectors are applied to the system with different time intervals (Ta, Tb, Tc) since these vectors are the nearest vector for V_{ref} [2]. The magnitude of the reference vector can be calculated as in Equation 1. The vectors m1 and m2 are horizontal and vertical projections of the vector. These can be found in Equation 1 and 2 respectively. From trigonometric calculations, boundary conditions of regions can be calculated as in Table 2.

$$m = \frac{Vref}{2Vdc/3} \tag{1}$$

$$m_1 = \frac{2}{\sqrt{3}} msin(\frac{\pi}{3} - \theta) \tag{2}$$

$$m_2 = \frac{2}{\sqrt{3}} msin\theta \tag{3}$$

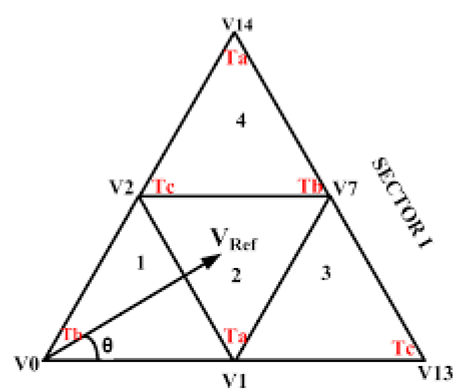

Fig. 3. Regions of Sector-1 of a three-level NPC inverter

The whole vector at other sectors but not sector 1 are calculated like in region 1 to generalize timing of vectors. The vectors are shifted to sector 1 first. After selection of the vectors switching in half period, time intervals of each vector should be determined to obtain exact magnitude and phase of reference vector [3].

TABLE 2
Logic used to find the region of Vref

m1 and m2	Region
m1<0.5, m2<0.5, (m1+m2)<0.5	I
m2>0.5	II
m1>0.5	III
m1<0.5, m2<0.5, (m1+m2)>0.5	IV

The For example, dwell time of Vref can be calculated as in Equation 4.

$$T_s V_{ref} = T_a V1 + T_b V7 + T_c V2 \tag{4}$$

The values of Ta, Tb and Tc can be calculated with respect to Table 3. These equations can be implemented to other sectors. However, to make simulation model simpler, the vector moves to sector 1 first.

TABLE 3
Region time formulas

Region	Ta	Tb	Tc
I	$2ksin(\frac{\pi}{3}-\theta)$	$T_s - 2ksin(\frac{\pi}{3}+\theta)$	$2ksin\theta$
II	$T_s - 2ksin\theta$	$2ksin\left(\frac{\pi}{3}+\theta\right) - T_s$	$T_s - 2ksin(\frac{\pi}{3}-\theta)$
III	$2ksin\theta - T_s$	$2ksin(\frac{\pi}{3}-\theta)$	$2T_s - 2ksin(\frac{\pi}{3}+\theta)$
IV	$2T_s - 2ksin(\frac{\pi}{3}+\theta)$	$2ksin\theta$	$2ksin\left(\frac{\pi}{3}+\theta\right) - T_s$

The last step of SV-PWM is the determine sequences of switches. According to sector and region, these sequences can be obtained according to efficiency of the system. In Table 4, all possible switching sequence for Sector I can be seen.

TABLE 4
Possible switching sequence for regions

Region	Switching Sequence
I	PPO-POO-OOO-OON-ONN
II	PPO-POO-PON-OON-ONN
III	POO-PON-PNN-ONN
IV	PPO-PPN-PON-OON

B. Field Oriented Control

The results of motor must be controlled to obtain desired speed and torque values. The control method that is used to reach desired output is called Field-Oriented Control (FOC) or vector control. In this method, phase currents and position of the motor are measured. Phase currents are transformed from stationary axes to rotating axes. The current values at rotating frame called id and iq currents. These current values can be calculated with respect to Torque formula of the IPMSM motor (Equation 5)

$$T_e = \frac{3}{2} pp(\psi_{pm} i_q - (L_d - L_q) i_d i_q) \tag{5}$$

These reference d-q currents are compared with the id and iq value of output currents. The error between them is minimized by using PI controller block. Then d-q voltages are calculated to find the reference vector. Vd and Vq can be found by using Equation 6 and Equation 7 respectively.

$$V_d = R_s i_d + L_d \frac{d}{dt} i_d - w_e L_q i_q \tag{6}$$

$$V_q = R_s i_q + L_q \frac{d}{dt} i_q - w_e (L_d i_d + \psi_{pm}) \tag{7}$$

The Simulink control block and obtaining Vd and Vq values of the inverter can be seen in Fig. 4.

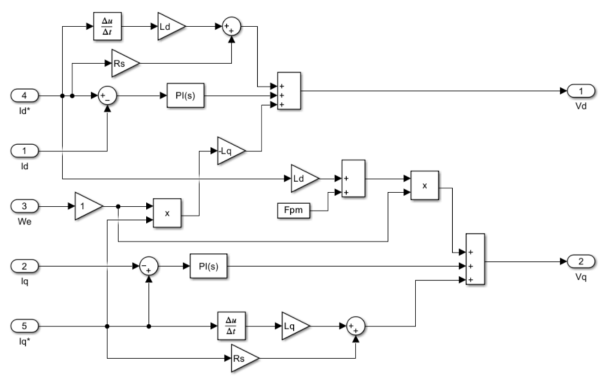

Fig. 4. Controller Block of 3-Level SV-PWM

In this simulation, maximum power of the system is 150kW and maximum torque is 280Nm. DC link voltage is 800V and maximum phase current peak is 280A. The base speed of the system can be found from maximum torque and maximum power. For this system it is 535.71. At maximum torque and base speed, I_d and I_q -176.48A and 180.42A, respectively. At half of the torque, I_d is -62.617A and I_q is 128.91A.

The switch is chosen for this simulation scenario as SEMiX302GAL12E4s. The voltage rating of this switch is 1200V and nominal current is 300A. The NP capacitor value is 222uF.

III. IPMSM Model Used in Simulation

The available permanent magnet synchronous machine model in Simulink is preferred to use as load in simulation. The block is given in Fig. 5. The motor properties entered to the machine model is given in the Table X. The given parameters belong to a real IPMSM. This section only includes used available model information and the model parameters.

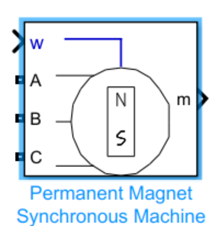

Fig. 5. Permanent magnet synchronous machine Simulink model

TABLE 5

IPMSM parameters

Parameter	Value
R_s	0.036 Ω
Ψ_{PM}	0.1383 Vs
L_d	473 μH
L_q	1155 μH
Number of poles	8
Number of phases	3

IV. Simulation Results and Comparison

The simulations results include the NP voltage ripple waveforms and line-to-line phase voltages, which are given in Fig. 6 and Fig. 7. The NP voltage ripple values as percentage of DC-link voltage is calculated by checking the peak-to-peak values of NP voltage ripple and given in the Table 6.

According to the simulation results, the neutral point ripple is related with the output load frequency and the output torque values. The ripple value is directly proportional to the output torque value and inversely proportional to the output load frequency. There is not a linear relation between the output torque, frequency, and NP voltage ripple amplitude. The neutral point voltage ripple is turning from sinusoidal to triangular waveform by domination of high order harmonics. However, the change could not be observed by the torque change with the figures.

The line-to-line voltage shapes are changing with the frequency. The frequency reduction causes dominant harmonic components. The line-to-line voltage shape is distorted by the reducing output frequency. The shape is seen as sinusoidal at higher frequency levels.

TABLE 6

NP voltage ripple values as percentage of DC-link Voltage

Case	Voltage Ripple	Voltage Ripple as percentage of DC-link voltage (800V) (%)
Max. Torq. / Base Speed	58	7.25
Half Torq. / Base Speed	38	4.75
Half Torq. / Half Base Speed	53	6.63
Half Torq. / ¼ Base Speed	80	10

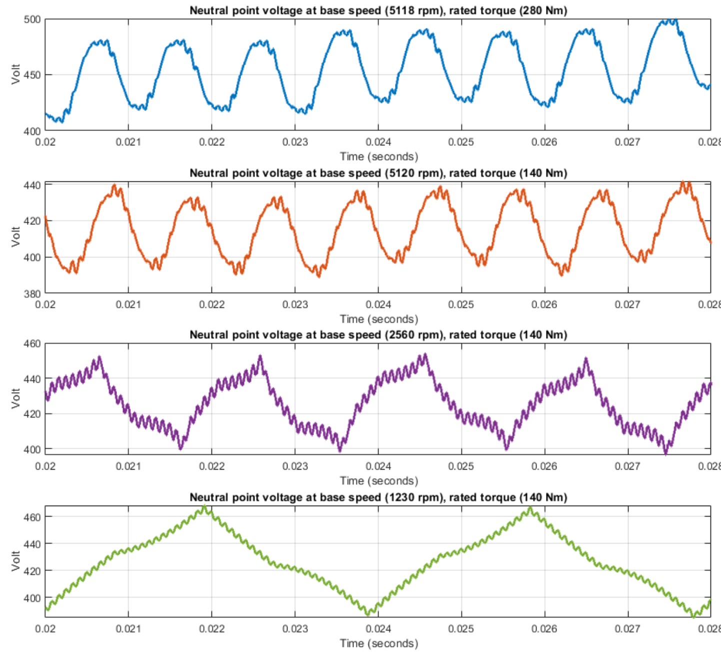

Fig. 6. Neutral point voltage ripple figures under different conditions

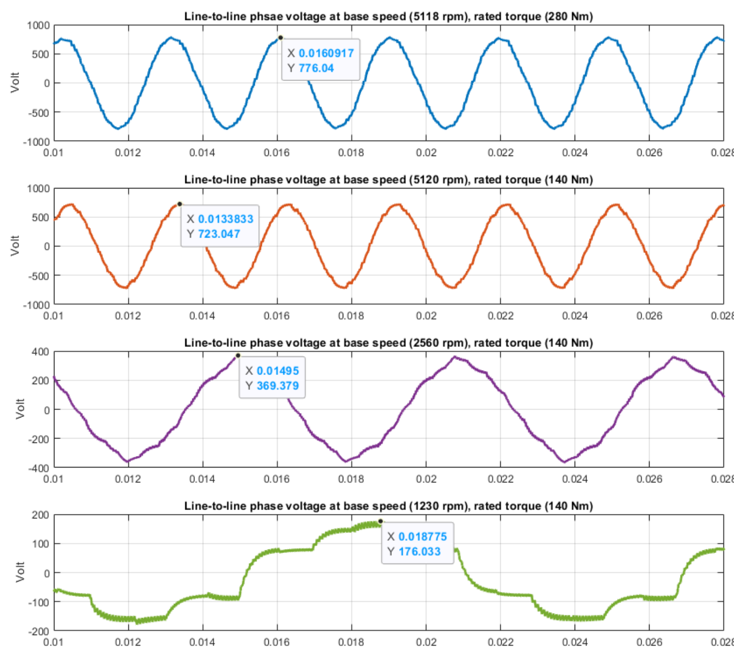

Fig. 7. Line-to-line voltage figures under different conditions

V. CONCLUSION

The output load frequency change under the same torque condition causes a change in the NP ripple amplitude. The ripple amplitude increases while the rotational speed of the IPMSM is reduced. In addition, under the same rotational speed condition, the NP ripple is higher with a higher torque value. In other words, the NP ripple is inversely proportional to the rotation speed and directly proportional to the output torque.

The high-order harmonics are dominated at the lowest rotational speed at NP and line-to-line voltages. From Fig. 6 and Fig. 7, the claim is obviously seen. However, the harmonic effect cannot be understood directly from the line-to-line and NP voltage waveforms, the harmonic content domination cannot be distinguished. The effect might be observed by doing fast Fourier transform (FFT) analysis on the voltage waveforms.

As additional information, the uncontrolled NP voltage ripple could cause some problems. For example, the ripple increases the voltage stress on the semiconductor switches. The operation life of semiconductors is shorted under long-term high-voltage stress. In addition, the semiconductor switches can see voltage difference, which is higher than the rated voltage of the switch, between their drain and source and it can cause malfunction of the switch. The ripple could also be responsible for the lower operation life of the neutral point capacitors. Finally, because of the rise in NP ripple, the output current total harmonic distortion (THD) increases. There are two possible approaches to limit the NP ripple at a safe level. Carrier-based PWM techniques and Active Neutral Point Voltage control. Selective Harmonic Elimination PWM technique could be used as a Carrier-based PWM technique to reduce and keep the ripple at a level. The neutral point voltage is sensed with active neutral point voltage control methods and the switching states of the inverter are arranged dynamically to maintain a stable and balanced neutral point ripple. Neutral point voltage modulation (NPVM) and Virtual Space Vector Modulation (VSM) are active neutral point voltage control method examples, which can be used for the purpose.

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