

# COMPARISON AND ANALYSIS OF THREE-LEVEL CONVERTERS VERSUS TWO-LEVEL CONVERTERS FOR SHIP PROPULSION APPLICATIONS

Hag Ahmed Y., Zhengming Zhao & Ting Lu

State Key Laboratory of Power System, Dept. of Electrical Engineering, Tsinghua University, Beijing, 100084, China

## ABSTRACT

In this paper, an overview of the techniques applied to AC electric propulsion field has been done. Actual study cases of electric ship propulsion schemes are considered. An impartial comparison between three-level converters versus two-level converter from the viewpoint of electric ship propulsion requirements has been done. Diode-clamped three-level converters using direct torque control (DTC) proved to be the most suitable converters for electric-ship propulsion compared to two-level converters. An attempt to represent the behavior of a ship's propulsion system comprising squirrel cage induction motor driven by a three-level converter has been conducted. The effectiveness of the system has also been verified through Psim 9.0.3 tools.

**Keywords:** *Electric ship propulsion, two and three-level converter, variable frequency drives (VFD), direct torque control (DTC).*

## 1. INTRODUCTION

In ships, the factors of reliability, economy, weight, space, cost, operation and maintenance are all involved in the propulsive equipment. Therefore, the most suitable types of drivers are those which excel in all or most important factors mentioned above [1], [2].

Main benefits of electric propulsion are, high overall efficiency, high availability, low operating costs, low maintenance, less installation and commissioning time and costs, size and weight savings, low noise and vibration levels, optimized machinery room design as well as improved power plant performance[3].

Electric propulsion has been applied to ships via direct current motors for more than a century. Except for some rare exceptions, on modern ships, the DC electrical machines have almost disappeared, certainly because of the complexity of their rotor, which increases drastically the life-cycle cost of the system[4].

Recent progress in power electronics has opened a new area in power conversion and has enabled the design of the high-performance medium voltage PWM converters. The concept of multilevel inverter control has opened a new possibility in which induction motors can be controlled to achieve a dynamic performance equal to that of dc motors in addition to its robustness, economic interest and efficiency [5].

Variable speeds of electric propulsion motors are operated from a variable frequency drive (VFD), which supplies power to motors at a frequency compatible with the desired speed. A typical arrangement of the electric network of a ship with electric propulsion motor is shown in Figure 1.

The Harmonic distortion has several deleterious effects, include causing insulation system to degrade and heating of generators winding, thus a good knowledge of the harmonic burden imposed by all power electronics equipment is necessary when it comes to designing systems and specifying equipment [6].

## 2. COMPARISON OF TWO AND THREE-LEVEL CONVERTERS

### 2.1 Two-level Converters

High power induction motor drives using a two-level converter has a number of features, including simple converter topology Figure 2, and various pulse-width modulation strategies, Fig.3. However, the inverter produces high  $d_v/d_t$  and high total harmonic distortion THD in its output voltage Figure 4-a. To improve these values; the switching frequency has to be raised, which in turn causes additional switching loss Fig. 4-b. Another possibility is to put a filter between the converter and the motor, which results in additional cost and weight. Switching frequencies and passive components are the two critical aspects affecting the performances of inverters. Higher switching frequency can lead to smaller-size passive components. However, the power loss of semiconductor switching devices will increase correspondingly [7]. Moreover, the dc link voltage of a two-level inverter is limited by voltage ratings of switching devices, the problematic series connection of switching devices is required to raise the dc link voltage. By series connection, the maximum allowable switching frequency has to be more lowered; hence, the harmonic

reduction becomes more difficult [11]. In addition, the two-level inverters generate high-frequency common-mode voltage within the motor windings which may result in motor and drive application problems [12].

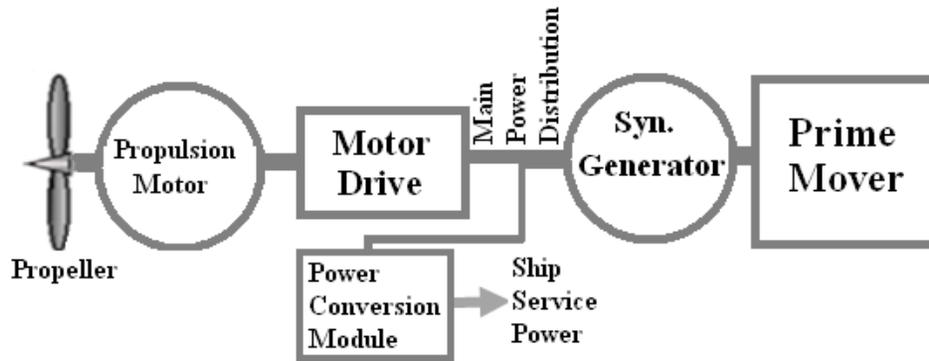


Figure 1: A typical arrangement of the electric network of a ship with electric propulsion motor

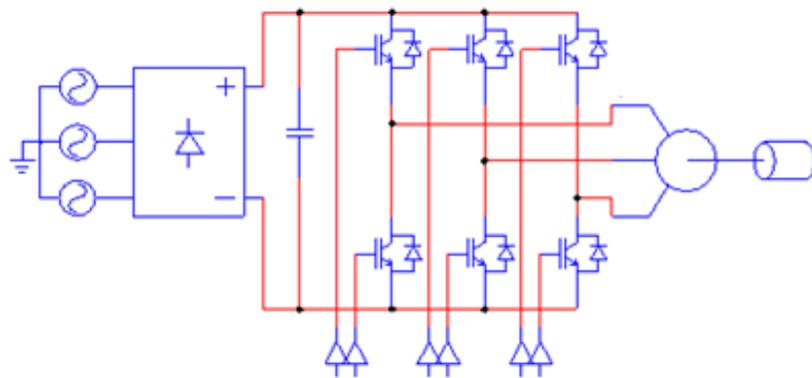


Figure: 2 Three Phase Two-level Converter

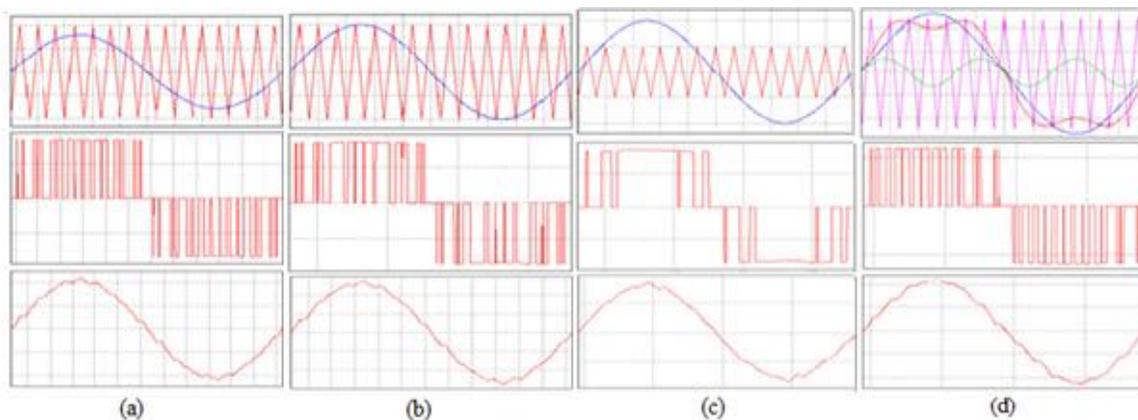


Figure: 3 Two-level converter PWM strategies (a)  $m_a = 0.8$  (b)  $m_a = 1$  (c) Over modulation (d) Third harmonic injection

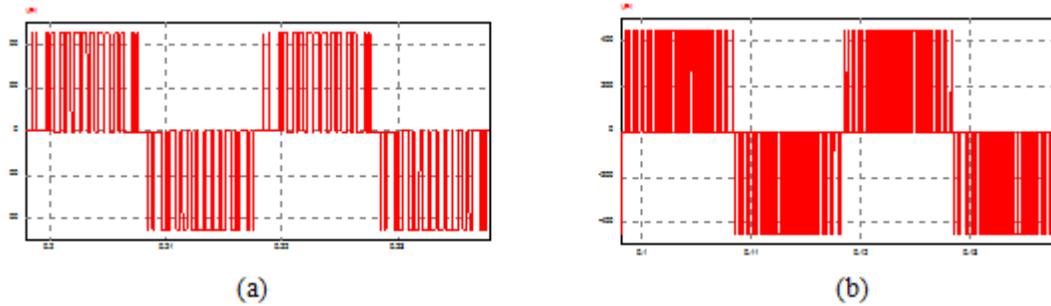


Figure 4: Two-level converter output voltage waveform (a) 750Hz switching Frequency (b) 1500Hz switching Frequency

**2.2 Three-level Converters**

Three-level converters were proposed in numerous configurations. The diode-clamped three-level converter[8], also known as the neutral point clamped multilevel converter, the flying-capacitor Three-level converter [8], further known as the imprecated cell converter, and the cascaded Three-level converter [8]. A comparison of these topologies is presented in [8] and [9].

Three-phase diode-clamped three-level converter topology and various pulse-width modulation strategies are shown in Figure 5, and Figure 6.

The main features of three-level converters are, offer better sinusoidal voltage waveform than two-level inverters because output voltage can be formed using three levels, as shown in Figure 7, this causes the THD to be lower, Low voltage switches can be used in three-level inverters; these are faster, smaller and cheaper than high-voltage switches used in 2-level inverters, when switches are in series; they withstand higher voltages, and when several voltage levels are used, the  $d_v/d_t$  of the output voltage is smaller thus the stress in cables and motor is smaller as well, and more importantly; the inverter can be used in the medium-voltage drive to reach a certain voltage level without switching devices in series[10].

As the number of level increases, the synthesized output waveform adds more steps, producing a staircase waveform. A zero harmonic distortion of the output wave can be obtained by an infinite number of levels. Unfortunately, the number of the achievable levels is quite limited not only due to voltage unbalance problems but also due to voltage clamping requirement, circuit layout and packaging constraints[11].

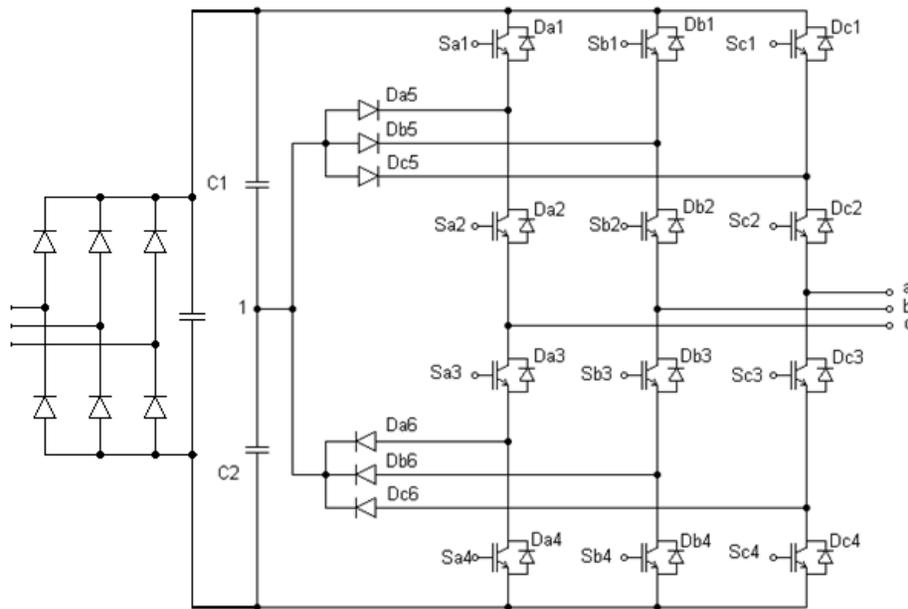


Figure 5: Diode-clamped three-level voltage source converter circuit.

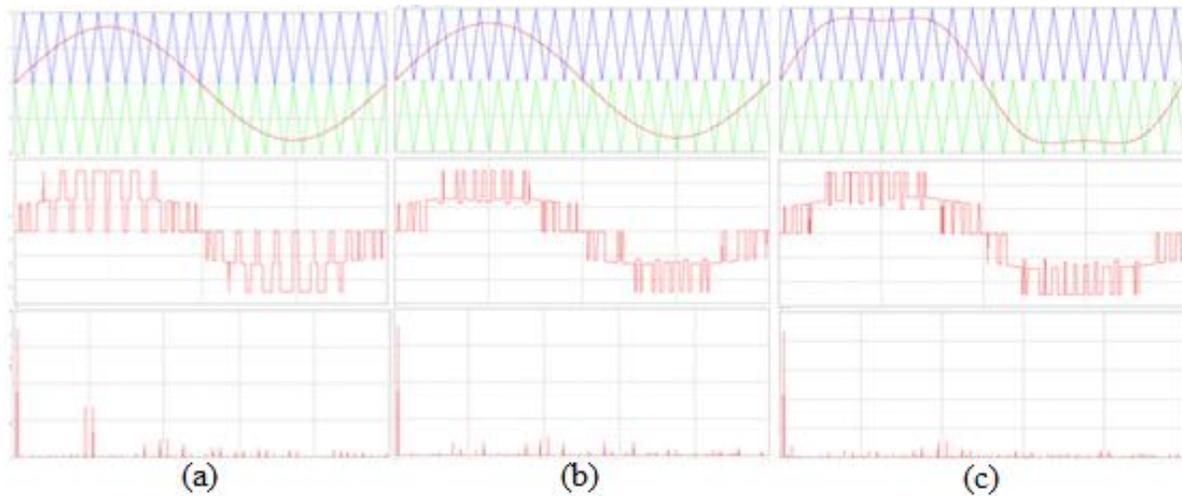


Figure 6: Three-level converter PWM strategies (a) Phase opposition disposition (POD) (b) Phase disposition (PD) (c) Third harmonic injection

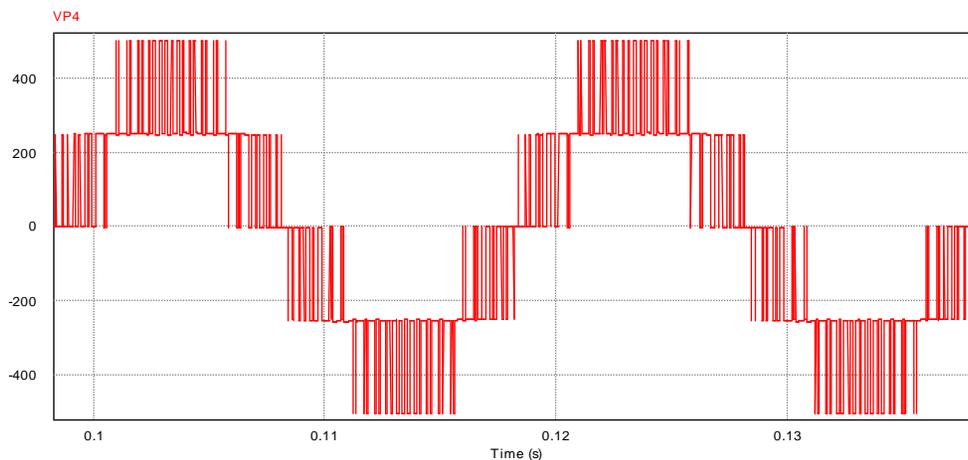


Figure 7: Three Phase diode-clamped Three-level Converter Output Voltage waveform

### 2.3 Cost Comparison

The costs of converters are dependent on lots of components such as the input inductor, AC filter capacitor, DC-link capacitor, IGBTs, fast diodes, heat sink, voltage sensor, control hardware, common mode filter, gate drives and snubbers. While, some cost comparison studies showed that the two-level converter configuration is around 25% and 27% cheaper than the three-level converter configuration (they just considered the price of main parts, IGBTs, DC-link capacitors and Diodes)[12] and [13], other's cost comparison studies showed that the three-level converter configuration is around 2% to 14% cheaper than that of two-level one depending on switching frequency ( they considered the price of all parts mentioned above ) [14].

### 2.4 Power Loss Comparison

The total power losses of switching devices are divided into two parts; conduction losses and switching losses. Power loss analysis in the two and three-level converters has been calculated extensively in several studies[12], [13], [15] and [16].

#### 2.4.1 Conduction losses comparison

Conduction losses occur while the power device is in the on-state and is conducting the current. They are dependent on the modulation index and power factor.

The conduction losses in an IGBT and an anti-parallel diode for two-level converters can be calculated as follows:

For an IGBT,

$$P_{Con.T} = \left( \frac{V_{OT} \times I_c}{2\pi} + \frac{r_{OT} \times I_c^2}{8} \right) + M \cos \varphi \left( \frac{V_{OT} \times I_c}{8} + \frac{r_{OT} \times I_c^2}{3\pi} \right) \quad (1)$$

Where  $r_{OT} = \frac{V_{CEN} - V_{OT}}{I_c}$

And for anti-parallel diode,

$$P_{Con.D} = \left( \frac{V_{OD} \times I_c}{2\pi} + \frac{r_{OD} \times I_c^2}{8} \right) + M \cos \varphi \left( \frac{V_{OD} \times I_c}{8} + \frac{r_{OD} \times I_c^2}{3\pi} \right) \quad (2)$$

Where  $r_{OD} = \frac{V_{FD} - V_{OD}}{I_c}$

The conduction losses in an IGBT and an anti-parallel diode for 3-level converters are:

For the two IGBTs,

$$P_{Con.T} = \left( \frac{V_{OT} \times I_c}{\pi} + \frac{r_{OT} \times I_c^2}{4} \right) + M \cos \varphi \left( \frac{V_{OT} \times I_c}{4} + \frac{r_{OT} \times I_c^2}{3\pi} \right) \quad (3)$$

And for anti-parallel diode,

$$P_{Con.D} = \left( \frac{V_{OD} \times I_c}{\pi} + \frac{r_{OD} \times I_c^2}{4} \right) + M \cos \varphi \left( \frac{V_{OD} \times I_c}{4} + \frac{r_{OD} \times I_c^2}{3\pi} \right) \quad (4)$$

Where  $I_c$  is the rated current,  $V_{CEN}$  is the rated collector-emitter voltage,  $V_{OT}$  is the threshold voltage of IGBT,  $V_{FD}$  is the diode voltage drop at rated current,  $V_{OD}$  is the threshold voltage of the diode (0.7V),  $M$  is modulation index ( $0 \leq M \leq 1$ ),  $\varphi$  is the power factor angle,  $r_{OT}$  is the IGBT forward resistance and  $r_{OD}$  is the Diode forward resistance. The total conduction losses of three-level converters are six times as much as that of the Two-level converters [12], [13] and [15]

### 2.4.2 Switching losses comparison

The more convenient way for calculating the switching losses is to utilize the switching energy-current (E-I) characteristic for on and off times of IGBTs and diodes. In fast recovery diodes anti-paralleled with the IGBTs, the turn-on losses of diodes are very few compared to the turn-off losses, so the turn-on losses of the diode can be neglected [9].

Switching losses for the IGBTs are:

$$P_{on+off} = \frac{1}{\pi} \cdot f_s \cdot [E_{on}(i) + E_{off}(i)] \quad (5)$$

Where,  $E_{on}$  is the on energy and  $E_{off}$  is the off energy, which are a function of the current.

Switching losses for the Diodes are:

$$i_d(t) = -I_1 \times (t - t_1) \times e^{-\alpha(t-t_1)^2} \quad (6)$$

Where

$$I_1 = \sqrt{2\alpha_1} I_{rr} e^{\frac{1}{2}}$$

$$\alpha_1 = \frac{1}{2(k t_{rr})^2}$$

$$k = \frac{t_{rra}}{t_{rr}}$$

In the period,  $t > t_2$ ,

$$i_d(t) = I_{rr} e^{-\alpha_2(t-t_2)^2} \quad (7)$$

Where,  $i_d$  is the diode current,  $\alpha_2$  is a constant which determines the rate at which the reverse recovery current decays less than 10% of  $I_{rr}$  at  $t_3$ . The total power loss of the three-level converter is lower than that of the two-level converters [12], [13].

## 3. SIMULATION RESULTS

The typical operation condition for the two and three-level converters such as, AC input voltage source, switching frequency, power factor, modulation index, frequency modulation index  $m_f$  and two identical three-phase induction motors were considered. 750 Hz switching frequency, modulation index  $m_a = 0.8$  and frequency modulation index  $m_f = 15$  were used for both types of converters. The simulation started by running the motor on no load at 600 rpm, then increasing the load torque and finally, increasing the speed to 1000 rpm. The simulation results revealed that the three-level converter could effectively control the induction motor speed and torque and enhances the drive performance Fig. 7. On the other hand, with two-level converter, the loaded motor failed to increase the speed from 600 to 1000 rpm Fig. 8-a. This happened due to inadequate voltage produced by the two-level inverter. That, the

torque developed by the motor is directly proportional to the magnetic field produced by the stator. So, the voltage applied to the stator is directly proportional to the product of stator flux and angular velocity[17].

The amplitude of the converter output voltage can be controlled by different methods such as variation of modulation index and changing the DC link voltage and so on [18]. Overmodulation, injected third harmonic component Fig. 3 and space vector pulse width modulation (SVPWM) can be used to boost the fundamental voltage and solve the problem of the speed increase Fig. 8-b., but overmodulation causes a reduction in the number of pulses in the line-to-line voltage waveform, leading to the emergence of low-order harmonics such as the 5th and 11th. However, the fundamental voltage is boosted to  $0.744V_d$ ; however, it is seldom used in practice due to the difficulties of filtering out the low-order harmonics.

The third harmonic component doesn't cause overmodulation, does not increase the harmonic distortion and does not exist in the line-to-line voltage as well. The maximum amount of fundamental voltage can be increased by this scheme is 15.5%, which is same as space vector pulse width modulation (SVPWM) [19],[20].

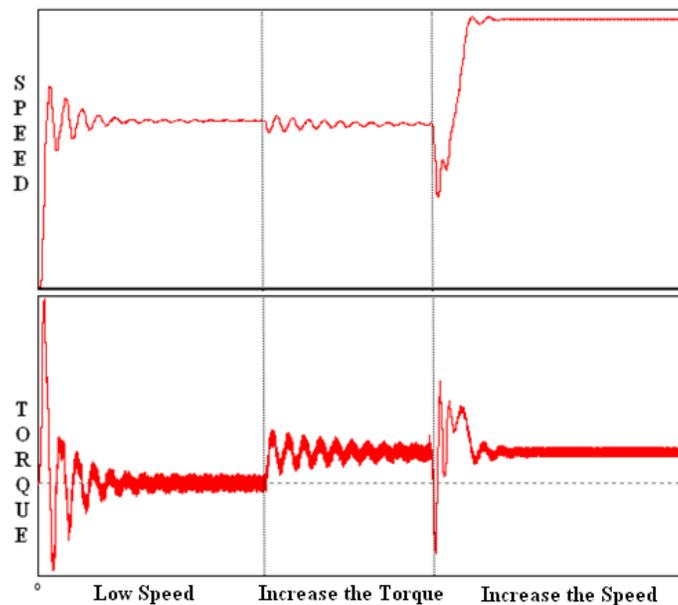


Figure 8: Speed-Torque curves for Three-level converter

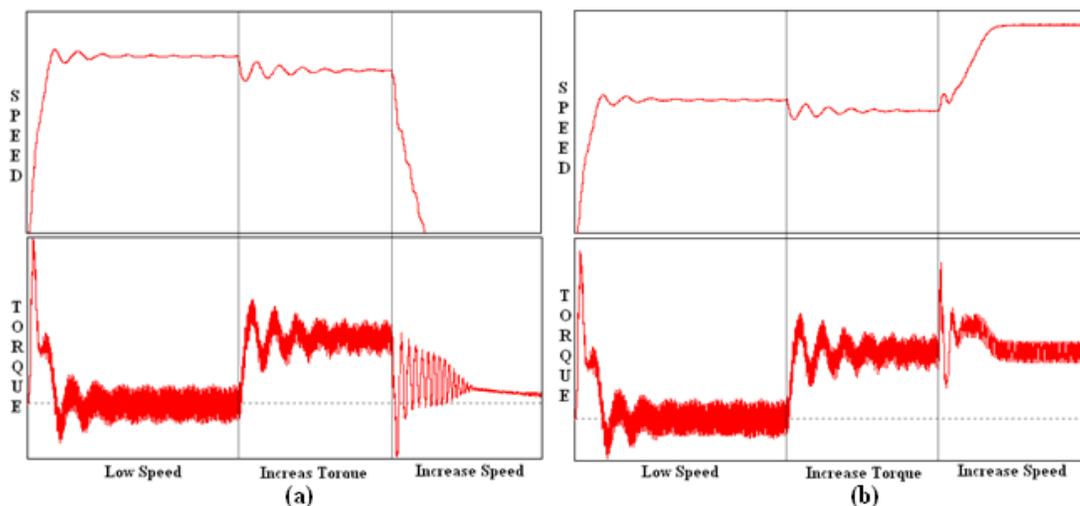


Figure 9: Speed-Torque curves for Two-level converter (a)  $m_a = 0.8$  (b)  $m_a = 2$  (over modulation)

## 5. THREE PHASE SQUIRREL CAGE INDUCTION MOTOR CONTROL

The developed AC motor control techniques can be grouped as, V/f (scalar) control, field vector control and direct torque control (DTC). The last two are the most sophisticated ones; hence they have been extensively exploited in the electric propulsion domain.

Direct Torque Control is a revolutionary motor control method for AC Drives, which allows accurate control of both motor speed and torque without pulse encoder feedback from the motor shaft, Fig.10. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor [21]. A comparison between open loop (PWM) control and DTC is shown in Figure 11.

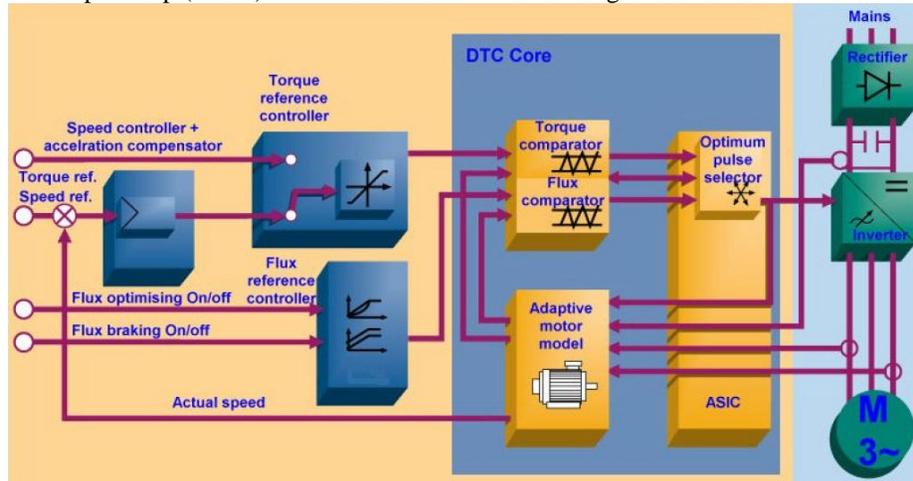


Figure 10: Direct torque control components

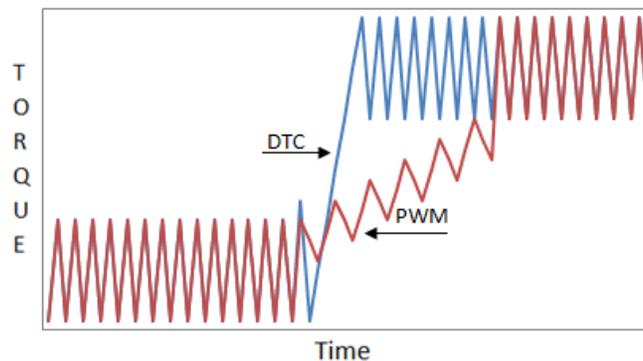


Figure 11: Torque response of DTC drive, compared with open loop PWM

## 6. DISCUSSION

Considering the results presented above, the following conclusions can be drawn:

The three-level converters are preferable to the two-level converters from the viewpoint of power losses.

Three-phase diode clamped three-level converter needs only one DC-bus while the others' three-level topologies need isolated DC supplies for each DC-bus, so it is suitable for ships amongst the others (space and cost factors). In ships, there are basic needs from the electric ship propulsion components; in which higher power capacity, high torque at low speed, and lower power losses are the most important targets. Direct Torque Control was chosen for electric ship propulsion application based on its low current distortion and fast torque response.

## 6. CONCLUSION

The diode clamped three-level converter is the most suitable multi-level topology for ship propulsion because of its high efficiency, better THD compared to the two-level converter. The simulation results have shown that three-level converter with DTC is the most appropriate for electric ship propulsion. The third harmonic component can be

implemented for boosting the output voltage of the two-level converter without causing overmodulation but it leads to the emergence of low-order harmonics.

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