Improvement of Direct Torque Control by using a Space Vector Modulation Control of Three-Level Inverter

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Abstract. The performances of Direct Torque Control (DTC) of Induction machine are highly related to the inverter used therewith. The purpose of this paper is to highlight the efficiency of the space vector modulation (SVM) control of three level inverter associated with the direct torque control. The first part of this work is devoted to present the mathematical models of the DTC associated with 2-levels inverter then 3-levels inverter. Simulations on Matlab/Simulink will allow a comparative study to highlight advantages of the use of three levels inverter. The second part is devoted to the improvement of the DTC associated with a 3-levels inverter by application of the space vector modulation strategy (SVM) in order to manage the switching frequency and reduce harmonics. The efficiency of this solution will be attested by simulation on Matlab/Simulink.

1. Introduction
The Direct Torque Control (DTC) of the induction machine is widely adopted in various industrial areas due to its simplicity, quick response, and robustness. However, the major problem of this command is high ripples of torque (and flux) caused by the hysteresis controllers. Many researches were achieved in order to improve and reduce torque ripples either by using multilevel inverters, space vector modulation, or using intelligent techniques. Reference [1] presents a novel Direct Torque Control of Induction Machine algorithm using a three-level Diode Clamped Inverter instead of the two level inverter used in the classical DTC scheme. Simulation results show that the proposed algorithm gives the same dynamical performances as those obtained with 2 level inverter with lower torque ripples. Reference [2] compares the performance of Direct Torque Control of Induction Machine using 2-level and 3-level inverter. The simulation results show that the torque and flux ripples were reduced using the three level inverter.

In reference [3], authors propose a space vector modulation SVM control of three-level inverter. Simulation and experimental results demonstrate that the proposed strategy permits to keep the harmonics centered on multiples of the switching frequency. Authors in reference [5] propose a solution for FPGA-based three level SVM inverter. The proposed strategy is verified by simulation in Matlab/Simulink. They also introduce the top-down methodology for FPGA design and give the functional block diagram for FPGA implementation.
This work investigates the efficiency of using multilevel inverter and Space Vector Modulation (SVM) in order to improve performances of DTC of the induction machine.

2. DTC USING 2 LEVEL AND 3 LEVEL INVERTER

2.1. Principal of DTC and mathematical model

The principal of the Direct Torque Control is based on the command of the inverter switches by applying a particular voltage sequence determining its status. The choice of the appropriate voltage vector depends on the machine’s electromagnetic state, it is obtained from the hysteresis controllers of flux and torque. It is therefore to maintain the torque and flux inside their hysteresis bands.

The principal scheme of DTC (figure 1) is composed of the induction machine, Estimation block, Hysteresis comparators (flux and torque), Switching table and Inverter.

![Figure 1. Principal scheme of Direct Torque Control (DTC) of induction machine](image)

The dynamic behavior of an induction machine in the stationary frame is described by the following state equations:

$$\begin{bmatrix}
\dot{\psi}_s^\alpha & \dot{\psi}_s^\beta
\end{bmatrix} = \begin{bmatrix}
\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & 0 & \frac{M}{\sigma L_s L_r T_r} & \frac{\omega M}{\sigma L_s L_r} & \frac{\omega r M}{M} \\
0 & \frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & -\frac{1}{\sigma L_s L_r} & \frac{1}{\sigma L_s L_r} & -\frac{\omega}{\sigma L_s L_r T_r} & 0 \omega r & -\frac{1}{\sigma L_s L_r T_r} & 0 & 0
\end{bmatrix} \begin{bmatrix}
\psi_s^\alpha & \psi_s^\beta
\end{bmatrix} + \begin{bmatrix}
\frac{1}{\sigma L_s} & 0 & \frac{1}{\sigma L_s L_r} & 0 & 0
\end{bmatrix} \begin{bmatrix}
\psi_o^\alpha & \psi_o^\beta
\end{bmatrix}$$

With

$$\sigma = 1 - \frac{M^2}{L_s L_r}$$

(1)

(2)
\[ Tr = \frac{Lr}{Rr} \]  

Mechanical equation:

\[ Tem = p^*(\psi_\alpha^*is\beta - \psi_\beta^*is\alpha) \]  

(4)

\[
\int \frac{d\Omega}{dt} = Tem - Tr - f^*\Omega
\]  

(5)

Estimation of flux and torque:

\[
\frac{d\psi_\alpha}{dt} = V_\alpha - is\alpha
\]  

(6)

\[
\frac{d\psi_\beta}{dt} = V_\beta - is\beta
\]  

(7)

\[
\psi^2 = \psi_\alpha^2 + \psi_\beta^2
\]  

(8)

\[
\arg(\psi) = a\tan(\psi_\beta/\psi_\alpha)
\]  

(9)

\[ Tem = p^*(\psi_\alpha^*is\beta - \psi_\beta^*is\alpha) \]  

(10)

Switching table:

The switching table allow to choose the appropriate voltage vector in order to maintain the flux and torque in their hysteresis bands. Determining the switch table depends not only on torque and flux hysteresis controllers and sector but also on the level of the inverter used the DTC command.

2.2. **Two Level inverter model and the switching table**

The operation of the two-level inverter follows a conduction sequence of 180 degrees by the switch of the same arm.

We note Si state of an arm (i= a,b,c).

- Si = 1; case when the switch of the top is closed and the lower one is opened.
- Si = 0; case when the switch of the top is opened and the lower one is closed.

Under this condition, the phase voltage can be written in accordance with the control signal Si:

\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} = \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_a \\
S_b \\
S_c
\end{bmatrix}
\]  

(11)

The different combinations of the three values (Sa, Sb, Sc) are used to generate eight voltage vectors: V0(000), V1(100), V2(110), V3(010), V4(011), V5(001), V6(101), V7(111).
Figure 2. Space vectors representation of the 2 level inverter output voltage

Table 1. Switching table for the 2 level inverter

| $\Delta \phi$ | $\Delta T_{em}$ | Sectors |
|----------------|-----------------|---------|
|                |                 | 1       | 2       | 3       | 4       | 5       | 6       |
| 1              | 0               | V2      | V3      | V4      | V5      | V6      | V1      |
| -1             | 1               | V6      | V1      | V2      | V3      | V4      | V5      |
| 0              | 0               | V0      | V7      | V0      | V7      | V0      | V7      |
| -1             | 0               | V5      | V6      | V1      | V2      | V3      | V4      |

2.3. Three-Level inverter and the switching table

The total voltage $U_{dc}$ of the DC input bus of the 3 level inverter is spread over two capacitors which form a middle point $o$, to obtain a higher voltage level. The three arms of the inverter are composed of four controlled switches ($K1$, $K2$, $K3$, and $K4$), these switches are unidirectional in terms of voltage and bidirectional in the current. The three-level inverter has three operating sequences:

- **Sequence 1**: maximum level generation
  
  K1 and K2 passing, k3 and k4 blocked:
  
  $V_{arm} = U_{dc}/2$
  
  $V_{k3} = V_{k4} = -E/2$

- **Sequence 2**: medium level generation
  
  K2 and k3 passing, k1 and k4 blocked:
  
  $V_{arm} = 0$
  
  $V_{k1} = V_{k4} = E/2$

- **Sequence 3**: minimum level generation
  
  K1 and K2 blocked, K3 and K4 passing
  
  $V_{arm} = -E/2$
  
  $V_{k1} = V_{k2} = E/2$

Table 2. Operating sequences of the three-level inverter

| K1 | K2 | K3 | K4 | Va0 |
|----|----|----|----|-----|
| 1  | 1  | 0  | 0  | E/2 |
| 0  | 1  | 1  | 0  | 0   |
| 0  | 0  | 1  | 1  | -E/2 |
The three-level inverter can be modeled as follows:

$$
\begin{align*}
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix}
= \frac{Udc}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix}
\begin{bmatrix}
F_{11} \\
F_{21} \\
F_{31}
\end{bmatrix}
- \begin{bmatrix}
F_{10} \\
F_{20} \\
F_{30}
\end{bmatrix}
\end{align*}
$$

(12)

With
Fk1: state of the top half arm
Fk0: state of the lower half arm
k: arm number
Fk1 = Sk1*Sk2 (states of switch 1 and 2 from arm k)
Fk0 = Sk3*Sk4 (states of switch 3 and 4 from arm k)

The output voltages of the three-level inverter can take three states (-1, 0 and 1) for the voltage levels (-Udc/2, 0 and Udc/2), it means that the voltage vector can take 27 states. The following figure represents the voltage vectors positions in the (α,β) reference.

Theses voltage vectors can be listed in four categories:
- Zero vectors: V0, V7 and V26
- Small vectors: V1, V2, V3, V4, V5, V6, V8, V9, V10, V11, V12, V13.
- Medium vectors: V20, V21, V22, V23, V24, V25.
- Large vectors: V14, V15, V16, V17, V18, V19.

| Vectors | states | Vectors | States | Vectors | States |
|---------|--------|---------|--------|---------|--------|
| V0      | 000    | V9      | -1-11  | V18     | 00-1   |
| V1      | 100    | V10     | 1-11   | V19     | -10-1  |
| V2      | 110    | V11     | 1-1-1  | V20     | -110   |
| V3      | 010    | V12     | 11-1   | V21     | 1-10   |
| V4      | 011    | V13     | -11-1  | V22     | 0-11   |
| V5      | 001    | V14     | -100   | V23     | 01-1   |
| V6      | 101    | V15     | -1-10  | V24     | 10-1   |
| V7      | 111    | V16     | 0-10   | V25     | -1-10  |
| V8      | -111   | V17     | 0-1-1  | V26     | -1-1-1 |
In this work, the switching table of the 3 level inverter fed DTC-IM drive considers only large, small and zero vectors.

### Table 4. switching table for the 3 level inverter

| Δflux | ΔTorque | Sectors |
|-------|---------|---------|
| -2    | V18     | V19     | V14 | V15 | V16 | V17 |
| -1    | V5      | V6      | V1  | V2  | V3  | V4  |
| 0     | V0      | V0      | V0  | V0  | V0  | V0  |
| 1     | V3      | V4      | V5  | V6  | V1  | V2  |
| 2     | V16     | V17     | V18 | V19 | V14 | V15 |
| -2    | V19     | V14     | V15 | V16 | V17 | V18 |
| -1    | V6      | V1      | V2  | V3  | V4  | V5  |
| 0     | V0      | V0      | V0  | V0  | V0  | V0  |
| 1     | V2      | V3      | V4  | V5  | V6  | V1  |
| 2     | V15     | V16     | V17 | V18 | V19 | V14 |

### 3. Space Vector Modulation

The principal of Space Vector Modulation (SVM) is based on the determination of time portions (modulation period) to be allocated to each voltage vector during the sampling period. The SVM is used to determine the ignition and extinction sequences of the inverter switches.

The proposed method is based on the predictive calculation of the stator voltage vector, applied to the induction machine to control the flux and torque, to determine the switching states of the inverter. It, therefore, provides an algorithm based on modulation of space vector for controlling the electromagnetic torque of the induction machine and provides a fixed switching frequency, it improves the dynamic response and static behavior of the DTC by reducing acoustic noises and torque, flux, current and speed ripples during steady state.

In the case of 3 level inverter, the space vectors diagram can be divided into 6 sectors (S1, S6), each sector can be divided into 4 triangles called region (figure 3). The SVM technique follows three steps:

- Determination of the voltage reference vector and the position.
4. Simulation and results

Simulations of DTC were carried out under Matlab/Simulink environment. For a nominal speed of 150 rad/s, we start the simulations with no load then apply a 35N.m load at $t=1$s.

Figure 4 show the torque response and a zoom of the no load part and the part with a load reference of 35N.m for classical DTC (2 level inverter) (a), DTC associated to 3 level inverter (b) and SVM – DTC associated with 3 level inverter (c).

In order to show the efficiency of the proposed method in reducing ripples, we calculated the harmonics magnitude (in % of the fundamental) for 10 frequency values and plot the results (figure 5).

Results presented in figure 4 show how the use of 3 level inverter (b) improved the classical DTC (a) by reducing torque ripples.

We notice a better improvement of torque response at figure 4 (c) where the SVM was introduced.
Figure 5. FFT analysis of torque response for the three methods

The FFT analysis in figure 5 also validates the efficiency of using SVM–DTC associated with a3-level inverter to reduce torque ripples. The Total Harmonic Distortion (THD) went from 71.5% in the classical DTC to 70% in DTC associated with 3 level inverter to reach 57.07% in SVM – DTC.

5. Conclusion
In this paper, we presented the model of classical DTC using 2 level NPC inverter, classical DTC using 3 level NPC inverter and SVM- DTC using three-level NPC inverter.

Simulation results under Matlab/Simulink environment show how the SVM-DTC gives better responses by reducing flux and torque ripples.

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