Direct torque control of an induction motor fed by a Quasi Z-source inverter

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Abstract

This study presents an adapted direct torque control (DTC) of an induction motor fed by a Quasi Z-source power inverter. Indeed, the Quasi Z-source structure is introduced in the power inverter in order to boost the DC-Link voltage. For this, the boost control is mainly based on the shoot-through states of the power inverter which two power switches can be turned on at the same time. In this context, a switching table for DTC is developed to ensure an independent control of the flux and the torque of the induction motor and to boost the DC-Link voltage. Thus, the sampling time should be shared alternatively between the boost of the DC-Link voltage and the control of the electromagnetic torque. Consequently, the developed system reduces both the boost floor and the number of the used power switches. Moreover, it ensures a high-performance induction motor control. The validation results have been carried out to prove the effectiveness of the developed control.

Keywords Quasi Z-source inverter · Direct torque control · Shoot-through states · Induction motor

1 Introduction

Recently, three-phase conventional inverters are widely used in many industrial applications. This prominence is due to their simplicity and high performance. In fact, they consist only of six bi-directional power switches (Diodes, Isolated Gate Bipolar Transistors-IGBT), DC-Link and control circuits. However, in different applications such as supplying a three-phase induction motor, the DC-link requires high voltage values. Overall, an additional boost floor is needed to have an adequate voltage value which can lead to complex electrical circuits. Moreover, in these conventional power inverters, two switches of the same leg can't be turned-ON at the same time. Thus, to avoid the DC-Link short-circuit, a dead-time is necessary for safe operations [1, 2]. These drawbacks can be overcome by inserting an impedance network to the power inverter. The new topology is called a Z-source structure which can give

more merits to the whole system. The proposed solution provides the desired output DC voltage and produces a ride through during voltage sags [3, 4].

In terms of control, many papers address this issue [5]. Authors present different Pulse Width Modulation techniques applied to the Z-source inverter and comparative investigations of Simple boost control (SBC), Maximum boost control (MBC), and Maximum constant boost control (MCBC) [6].

In this paper, the developed system concerns the adaptation of the Direct Torque Control to an induction motor fed by a Quasi Z-source inverter.

In many industrial applications such as electric vehicles, photovoltaic energy, and Full cell systems, the power electronics converter system is composed of DC-DC converters to boost the output voltage and DC-AC converters to control the induction motor. These converters suffer from the number of power switches, weight, and cost of the

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system [7, 8]. So, to overcome these drawbacks, another solution can be envisaged by using a Z-source structure which consists of impedance networks (Inductances and capacitors) instead of the DC–DC converter. In this structure, the DC–AC converter can ensure at the same time the voltage boost and the induction motor control operation modes [9, 10]. However, in the Z-source structure, the same high voltage is applied to the two capacitors while in Quasi Z-source, the voltage applied on one of the two capacitors is lower, which requires a lower capacitor rating. Moreover, in the Quasi Z-source structure, the input current is continuous due to the inductance, which reduces input ripples.

In the other hand, to supply an induction motor by using a Quasi Z-source inverter, a specified control should be required. So, the two operation modes (boost task and the control of the induction motor) should be ensured.

Fig. 1 Quasi Z-source Inverter structure

For this, the sampling time is divided between the boost and control operation modes. For the control operation modes, many control techniques can be used such as the Indirect Field Oriented Control (IFOC) [11]. In this context, regarding of the simplicity of implementation, this paper adopts the direct torque control [12]. For this, the adapted switching table is developed for both operation modes. In fact, an appropriate voltage vector should be chosen to ensure the load control while the boost task is ensured by the insertion of the null voltage vector to the three-phase inverter [13].

2 Quasi Z-source structure

Figure 1 shows a Quasi Z-source inverter structure. It consists of DC-link voltage, two inductances (L_1 , L_2), two capacitors (C_1 , C_2), a diode and three-phase inverter.

In this structure, two power switches (IGBT) of the same leg can operate at the same time to boost the DC-link voltage. In this context, shoot-through states are inserted during the zero states of the three-phase inverter. Moreover, the impedance network (inductances and capacitors) operates also as a filter that limits the current ripples during the shoot-through states [14].

Typically, a conventional three-phase power inverter has six active states and two zero states. However, the Quasi Z-source structure has six active states, two zero states and seven shoot-through states such as given by Table 1. The shoot-through states are provided by the short-circuit of each power leg to give three states, two legs to obtain three states) and three legs provide one state of the Quasi Z-source three-phase inverter.

Table 1 Quasi Z-source inverter states

States	States of the switches					
	K11	K21	K31	K10	K20	K30
Active	1	0	0	0	1	1
	1	1	0	0	0	1
	0	1	0	1	0	1
	0	1	1	1	0	0
	0	0	1	1	1	0
	1	0	1	0	1	0
Zero	1	1	1	0	0	0
	0	0	0	1	1	1
Shoot through	1	0	0	1	0	0
	0	1	0	0	1	0
	0	0	1	0	0	1
	1	1	0	1	1	0
	1	0	1	1	0	1
	0	1	1	0	1	1
	1	1	1	1	1	1
	1	1	1	1	1	1

Fig. 2 Quasi Z-source shoot-through states equivalent circuit

Fig. 3 Quasi Z-source inverter active states equivalent circuit

The role of the Quasi Z-source structure is to ensure, at the same time, a DC to AC conversion and boost the DC-link voltage like the step-up chopper. This operating mode can be analyzed by using an equivalent circuit, where both three-phase six-switch inverter and load are represented by one single switch (K) in parallel with a single-phase load [15].

The Quasi Z-source network operates in two states: shoot-through states (Fig. 2) and no shoot-through states (Fig. 3).

In the no-shoot-through or active states, the load is supplied by the DC-link voltage. However, in the shoot through or zero states, the Quasi Z-source structure increases the voltage across the capacitors.

The shoot-through states can be presented by the following equations:

$$\begin{cases} V_{L1} = V_{C2} - V_e \\ V_{L2} = V_{C1} \\ V_i = 0 \end{cases} \quad (1)$$

Active states can be expressed by the equations:

$$\begin{cases} V_{L1} = V_e - V_{C1} \\ V_{L2} = -V_{C2} \\ V_i = V_{C1} - V_{L2} \\ V_i = V_{C1} - V_{C2} \end{cases} \quad (2)$$

The average value of the inductance voltage $\langle V_L \rangle$ during this sampling time should be zero, and it is given by the following relation:

$$\begin{aligned} \langle V_{L1} \rangle &= \langle V_{L2} \rangle \\ &= \frac{T_0 \times (V_{C2} - V_e) + (T - T_0) \times (V_e - V_{C1})}{T} = 0 \end{aligned} \quad (3)$$

$$\langle V_{C2} \rangle = \frac{T_0 \times V_{C1} + (T - T_0) \times (-V_{C2})}{T} \quad (4)$$

It is assumed that the duration of the shoot-through states is T_0 where T represents the sampling time.

From the previous equation, V_{C1} and V_{C2} can be expressed by:

$$V_{C1} = \frac{(T - T_0)}{(T - 2 \times T_0)} \times V_e \quad (5)$$

$$V_{C2} = \frac{T_0}{(T - 2 \times T_0)} \times V_e \quad (6)$$

The expression of the maximum value of the voltage V_i is given as:

$$V_i = V_{C1} + V_{C2} = \frac{T}{(T - 2 \times T_0)} \times V_e \quad (7)$$

Based on the above analysis, the Quasi Z-source inverter merits are better than in the Z-source structure. It can ensure the buck-boost modes and able to operate at shoot-through states. It is unnecessary to add a dead band into the control system, which reduces the output distortion. In addition, in Z-source, the same high voltage is applied to the two capacitors while in Quasi Z-source, the voltage on the capacitor (C_2) is lower, which requires a lower capacitor rating. So, Z-source inverter has discontinuity input current in the boost mode, while in Quasi Z-source, the input current is continuous due to the inductor L_1 , which reduces input stress [16].

2.1 Impedance network sizing

In Quasi Z-source topology, determining values of inductances (L_1 and L_2) and capacitors (C_1 and C_2) is an important and critical step that represents the key factor and has a great influence on the output voltage V_i . It allows

increasing the DC input voltage and their values should be chosen with respect to the following equations [17]:

$$L \geq \frac{d \times (1 - d)}{\Delta i_L \times f_m \times (1 - 2 \times d)} \times V_{dc} \quad (8)$$

$$C \geq \frac{P \times d}{V_{dc} \times f_m \times \Delta V_C} \quad (9)$$

where $d = \frac{T_{cc}}{T}$.

3 Direct torque control of quasi Z-source inverter fed induction motor

The main objective of the developed control is to ensure the DC-Link voltage boost and the control of the induction motor fed by a Quasi Z-source inverter. The boost task is ensured by an impedance network while the induction motor control is based on the direct torque control with hysteresis controllers. However, many control techniques such as backstepping and sliding mode can be used instead of the hysteresis controllers in order

to improve the performance of the developed system [18, 19]. In the literature, many works use backstepping and sliding mode techniques to control the stability and enhance the dynamics of the induction motors. So, the sliding mode is more suitable for systems with modeling uncertainties and variable parameters, or with the presence of large external disturbances. However, these control techniques suffer from chattering phenomena and the choice of the gains [20, 21].

3.1 Direct torque control principle

Direct Torque Control is based on the selection of a voltage vector to control flux and torque values using hysteresis controllers [22].

Figure 4 shows the direct torque control scheme in which the control sequences are applied to the power switches. The control sequence is provided by the switching table to select the output voltage of the inverter [23, 24].

The stator flux in the induction motor is given in the stationary reference frame (α, β) by [25]:

Fig. 4 Direct torque control scheme

$$\bar{V}_s = R_s \bar{I}_s + \frac{d\bar{\phi}_s}{dt} \quad (10)$$

$$\text{With: } \bar{\phi}_s = \int_0^t (\bar{V}_s - R_s \bar{I}_s) dt \quad (11)$$

For high speeds, the voltage drop can be neglected due to the stator resistance.

$$\bar{\phi}_s = \bar{\phi}_{s0} + \int_0^t \bar{V}_s dt \quad (12)$$

During each sampling time, the voltage vector to be applied is constant [26]:

$$\Delta \bar{\phi}_s = \bar{V}_s T_e \quad (13)$$

The error of the stator flux $\Delta \bar{\phi}_s$ is linear with the voltage stator vector for a constant sampling time.

The stator flux amplitude is kept in the hysteresis band around its reference. The rotor flux amplitude will also be approximately constant when the flux is established in the motor. The flux estimation can be carried out based on current and voltage measurements [27].

The torque is the vector product of the stator and rotor flux vectors according to the equation:

$$\Gamma_e = K(\bar{\phi}_s \times \bar{\phi}_r') = K \bar{\phi}_s \bar{\phi}_r' \sin \theta_{sr} \quad (14)$$

$$\text{Or: } K = p \frac{M}{L_s L_r}$$

$$\begin{cases} V_{s\alpha} = r_{s\alpha} i_{s\alpha} + \frac{d\phi_{s\alpha}}{dt} \\ V_{s\beta} = r_{s\beta} i_{s\beta} + \frac{d\phi_{s\beta}}{dt} \end{cases} \quad (15)$$

The stator flux is expressed by:

$$\begin{cases} \phi_{s\alpha} = \int_0^t (V_{s\alpha} - r_{s\alpha} i_{s\alpha}) dt \\ \phi_{s\beta} = \int_0^t (V_{s\beta} - r_{s\beta} i_{s\beta}) dt \end{cases} \quad (16)$$

In Concordia transformation, voltages ($V_{s\alpha}$, $V_{s\beta}$) are obtained from the following equations:

$$\bar{V}_s = V_{s\alpha} + jV_{s\beta} \quad (17)$$

Figure 5 shows the voltage vectors of the three-phase inverter representation.

$$\begin{cases} v_{s\alpha} = \sqrt{\frac{2}{3}} V_{dc} \left(S_a - \frac{1}{2}(S_b + S_c) \right) \\ v_{s\beta} = \frac{1}{\sqrt{2}} V_{dc} (S_b - S_c) \end{cases} \quad (18)$$

Fig. 5 Voltage vectors representation

The current components ($i_{s\alpha}$, $i_{s\beta}$) in Cocordia fram are calculated by the phase currents i_a , i_b , i_c [28]:

$$\bar{I}_s = i_{s\alpha} + j i_{s\beta} \quad (19)$$

$$\begin{cases} i_{s\alpha} = \sqrt{\frac{2}{3}} i_a \\ i_{s\beta} = \frac{1}{\sqrt{2}} (i_b - i_c) \end{cases} \quad (20)$$

The flux amplitude and angle are obtained by:

$$\hat{\phi}_s = \sqrt{\hat{\phi}_{s\alpha}^2 + \hat{\phi}_{s\beta}^2} \quad (21)$$

$$\theta_{sr} = \arctg \frac{\phi_{s\beta}}{\phi_{s\alpha}} \quad (22)$$

The number of the flux sector is detected by the angle θ_{sr} and the stator components (Fig. 6) [29, 30].

Table 2 presents the switching table with non-active voltage vectors.

3.2 DTC-based Shoot-through control

In the developed control of the Quasi Z-source inverter, the shoot-through vector is inserted in zero states of the three-phase inverter. However, the duration of the zero states (V_0 or V_7) can't be enough to boost the DC-Link voltage. Indeed, the control sequences are applied during a modulation period T_m such as [31]:

$$T_m = K \times T_e \quad (23)$$

K: is an integer to be determined.

Fig. 6 Sectors detection

The insertion of the shoot-through state of the power leg inverter is performed by:

$$T_{\%} = d \times T_m \quad (24)$$

With: $0 \leq d \leq 100\%$.

During the remaining time $((1-d)T_m)$ the direct torque control is applied (Fig. 7).

Where $T_{DTC} = (1-d)T_m$ is the DTC time and $T_{ST} = dT_m$ is the shoot-through time.

The duty ratio "d" is chosen to increase the DC-bus voltage by keeping the performance of the direct torque control in terms of flux and torque ripples. For this, the control time (T_m) is shared between the DC-bus voltage control and the DTC strategy. Nevertheless, if the duty ratio is relatively small which means a sufficient application time of the DTC strategy T_{DTC} then the performance of the direct torque control can not be affected. Hence, the shoot through the duration T_{ST} should be determined in order to regulate the DC-bus Voltage.

Fig. 7 Shoot-through states application

Table 3 DTC Quasi Z-source switching table

Sector		N=1	N=2	N=3	N=4	N=5	N=6
$C_T=1$	$C_T=1$	V_2	V_3	V_3	V_5	V_6	V_1
	$C_T=0$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}
	$C_T=-1$	V_7	V_0	V_7	V_0	V_7	V_0
	$C_T=1$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}
	$C_T=0$	V_6	V_1	V_2	V_3	V_4	V_5
	$C_T=-1$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}
$C_T=0$	$C_T=1$	V_3	V_4	V_5	V_6	V_1	V_2
	$C_T=0$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}
	$C_T=-1$	V_0	V_7	V_0	V_7	V_0	V_7
	$C_T=1$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}
	$C_T=0$	V_5	V_6	V_1	V_2	V_3	V_4
	$C_T=-1$	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}	V_{ST}

The switching table of the direct torque control for Quasi Z-source inverter is shown in Table 3. It summarizes the insertion of the active and shoots through states.

V_{ST} : Represents the application of the shoot-through states. To increase the duration of the shoot-through the voltage vector V_0 can be replaced by V_7 . DC bus control.

3.3 DC bus regulation

The DC bus voltage can be controlled by using both voltages across the capacitor (V_c) and across the input of the inverter (V_i) [32]. Regarding simplicity and effectiveness,

Table 2 DTC switching table

Flux	Torque	Sector					
		1	2	3	4	5	6
$S_{\phi s}=1$	$S_{\phi s}=1$	$V_2(1,1,0)$	$V_3(0,1,0)$	$V_4(0,1,1)$	$V_5(0,0,1)$	$V_6(1,0,1)$	$V_1(1,0,0)$
	$S_{\phi s}=0$	$V_7(1,1,1)$	$V_0(0,0,0)$	$V_7(1,1,1)$	$V_0(0,0,0)$	$V_7(1,1,1)$	$V_0(0,0,0)$
$S_{\phi s}=0$	$S_{\phi s}=1$	$V_3(0,1,0)$	$V_4(0,1,1)$	$V_5(0,0,1)$	$V_6(1,0,1)$	$V_1(1,0,0)$	$V_2(1,1,0)$
	$S_{\phi s}=0$	$V_0(0,0,0)$	$V_7(1,1,1)$	$V_0(0,0,0)$	$V_7(1,1,1)$	$V_0(0,0,0)$	$V_7(1,1,1)$

Fig. 8 Regulation algorithm of the DC-Link

this paper deals with a hysteresis controller to ensure enough shoot-through time and DC bus voltage (V_i). The flowchart of this algorithm is shown in Fig. 8.

The decision is divided into four steps:

For this we define ε as: $\varepsilon = \frac{V_{ref} - V_i}{V_{ref}}$.

If ε is negligible, no shoot-through is applied.

Else if ε has a small value, α_1 of shoot-through is applied.

Else if ε has a medium value, α_2 of shoot-through is applied, else the maximum shoot-through (α_3) is applied.

4 Validation results

The obtained results have been carried out by mean of an induction motor associated with an impedance network-based inverter, in which the parameters are given in the "Appendix". For this, the sampling time of the control has been divided between the boost process in order to insert the shoot-through states and the direct torque control for the induction motor.

In Fig. 9, it can be shown both of DC-Link voltage (V_{dc}) before and after boosting (V_i). Figure 10 presents the line to line voltage (V_{ab}) applied to the induction motor.

Fig. 9 DC-Link voltage V_i and reference voltage (V_{dc})

Fig. 10 Line to line voltage V_{ab}

Fig. 11 Inductance current I_i

Fig. 12 Capacitor voltage V_{Cz}

Fig. 14 Induction motor Torque

Fig. 13 Phase currents i_a , i_b and i_c

Fig. 15 Speed response

Figures 11 and 12 show respectively the inductance current (I_L) and the voltage across the capacitor (V_{Cz}).

Figure 13 shows the absorbed sinusoidal current which proves the performance of the developed direct torque control.

Figures 14 and 15 show respectively the electromagnetic torque and speed responses.

Figure 16 shows the trajectory of the stator flux.

5 Results discussion

In the boost control mode, the DC input voltage is amplified with an elevation gain of $G = 5.5$ as shown in Fig. 9. So, the impedance network (inductances and capacitors) ensures the operation of the DC/DC converter in a conventional system and therefore reduces the number of power switches in the developed system. Moreover, as given by Fig. 11, it can be seen that the inductance current ripples are reduced in the Quasi Z-source inverter compared with the Z-source structure [33]. For this, during the shoot-through states, the current i_L is increased, and the two inductances are fully charged, while during the active states the current i_L decreased because of

Fig. 16 Flux trajectory

the two inductances restore their energy to the power inverter. In Quasi Z-source, the capacitor voltage has less stress voltage compared with the Z-source topology (Fig. 12) [34–37].

In Fig. 15, the speed response follows its reference. In the induction motor control, direct torque control is used to guarantee an independent control of the flux and the torque. For this, the flux and torque follow well the given references with a high dynamic response (Figs. 14, 16). Moreover, through the DTC the induction motor absorbs a sinusoidal current which illustrates the performance of the developed system as given by Fig. 13.

It can be noticed that, in both operation modes (boost and DTC), the period of each task should be accurately chosen in order to get high-performance control of the whole system.

6 Conclusions

In this paper, an adapted direct torque control of an induction motor fed by a Quasi Z-source inverter has been presented. For this, a switching table is developed to ensure at the same time the induction motor control and the DC-Link voltage boost. Hence, the sampling time is divided between the shoot-through states and the direct torque control. Thus, The developed control reduces the boost floor and therefore the number of power switches. Finally, the validation results have been carried out to prove the effectiveness of the developed control.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Rated data of the simulated induction motor

$P = 4 \text{ kW}$, $n = 1420 \text{ rpm}$, $p = 2$.

$R_s = 1.823 \Omega$, $R_r = 3.2422 \Omega$, $L_s = 0.2289 \text{ H}$, $L_r = 0.2289 \text{ H}$, $L_m = 0.2198 \text{ H}$, $J = 4.1587 \cdot 10^{-3} \text{ kg.m}^2$, $k_f = 1.277 \times 10^{-3} \text{ Nms/rd}$.

Impedance network parameters.

$V_{dc} = 100 \text{ V}$, $L = 3.2 \text{ mH}$, $C = 1200 \text{e-}3 \text{ F}$, $r = 1 \Omega$.

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