

http://www.itrans24.com/landing1.html

Electr Eng DOI 10.1007/s00202-016-0472-4

ORIGINAL PAPER



### High-performance multicell series inverter-fed induction motor drive

M. Khodja<sup>1</sup> · D. Rahiel<sup>2</sup> · M. B. Benabdallah<sup>3</sup> · H. Merabet Boulouiha<sup>1,3</sup> · A. Allali<sup>3</sup> · A. Chaker<sup>2</sup> · M. Denai<sup>4</sup>

Received: 23 June 2016 / Accepted: 2 November 2016 © Springer-Verlag Berlin Heidelberg 2016

Abstract The multilevel voltage-source inverter (VSI) topology of the series multicell converter developed in recent years has led to improved converter performance in terms of power density and efficiency. This converter reduces the voltage constraints between all cells, which results in a lower transmission losses, high switching frequencies and the improvement of the output voltage waveforms. This paper proposes an improved topology of the series multicell inverter which minimizes harmonics, reduces torque ripples and losses in a variable-speed induction motor drive. The flying capacitor multilevel inverter topology based on

🖂 M. Denai m.denai@herts.ac.uk M. Khodia

> khodja1970@gmail.com D. Rahiel

rahiel\_djelloul@yahoo.fr M. B. Benabdallah benabdallah22@yahoo.fr

H. Merabet Boulouiha houari.merabet@gmail.com

A. Allali allalia@yahoo.com

A. Chaker chakeraa@yahoo.fr

1 Centre universitaire de Relizane Ahmed Zabana CUR-AZ, Relizane, Algeria

- 2 Ecole Normale Polytechnique d'Oran ENPO, Oran, Algeria
- 3 Laboratoire de Développement Durable de l'Energie Electrique, Faculté de Génie Electrique, Département d'Electrotechnique, LDDEE, Université des Sciences et de la Technologie d'Oran, Mohamed Boudiaf, Oran, Algeria
- 4 School of Engineering and Technology, University of Hertfordshire, Hatfield AL10 9AB, UK

the classical and modified phase shift pulse width modulation (PSPWM, MPSPWM) techniques are applied in this paper to minimize harmonic distortion at the inverter output. Simulation results are presented for a 2-kW induction motor drive and the results obtained demonstrate reduced harmonics, improved transient responses and reference tracking performance of the voltage in the induction motor and consequently reduced torque ripples.

Keywords Multicell converter · Induction machine · Phase-shift PWM · Indirect vector control · Fuzzy logic control

#### **1** Introduction

Many variable-speed induction motor drive applications require high torque dynamics and low torque ripples to meet the requirements of high productivity and improved accuracy. In commercial variable-speed induction motor drives, two control schemes based on field-oriented control (FOC) [1-3] and direct torque control (DTC) [4] have been widely for more than two decades.

DTC [5,6] has proved to be a very effective method for the control of induction machines. As compared to field-oriented control (FOC), DTC implementation minimizes the use of machine parameters [7,8] while maintaining the advantages of fast transient response characteristics. Nevertheless, these two control techniques have a major disadvantage as they exhibit ripples at high torque and flux values which also results in high acoustic noise [9].

In the early 1990s, a new structure of multilevel converters has been proposed [10,11]. This structure is based on the series connection of switching cells between which a floating voltage source is inserted. These floating voltage sources are

realized with capacitors. The series multicell structure can be adapted to all types of configurations including chopper or inverter with a capacitive medium point, half bridge or full bridge.

Multilevel inverters are becoming essential to achieve high-quality output voltages with a substantial reduction in the total harmonic distortion (THD). The overall size of the converter is also reduced and consequently these converter types are becoming very popular and are being used in a wide range of industrial applications in recent years [12–24].

In [25], a sliding mode control (SMC) based on indirect field-oriented control (IFOC) was applied to control the speed of an induction motor using a dSPACE DS1104 interface card.

A medium voltage five-level NPC (Neutral Point Clamped) inverter-fed induction motor for industrial applications has been studied in [26,27]. The inverter is supplied by a Z-type source to provide more flexibility for the DC current. The induction motor control is based on DTC. A comparative study between a conventional PI (proportional-integral) and fuzzy logic control (FLC) of the induction motor has been studied in [28]. In [29], model predictive control (MPC) is applied to a multicell converter. The control strategy has been tested both in simulations using Matlab/Simulink and validated experimentally using a dSPACE card.

A comparative study of three DTC control methods for a squirrel cage induction generator (SCIG) was presented in [30]. Namely, the classical DTC, the DTC-SVPWM fixed frequency inverter with two level and three-level NPC topologies. The switches are controlled by three-level SVPWM which takes into consideration the balancing the DC link voltage.

In this paper, rotor flux oriented vector control of the induction motor based on a series multicell converter is proposed to improve the quality of the three-phase currents and consequently minimizing torque ripples.

This paper is organized as follows: Sect. 2 describes the topology of the flying capacitor multilevel inverter (FCMI) driving an induction motor and presents the generalized switching law for FCMI based on the phase-shifted PWM (PSPWM) strategy. Section 3 describes the arrangement for a general simulation model and develops the control design of the induction motor based on indirect field-oriented control (IFOC) using both a classical PI and FLC controllers. The simulation results for the conventional and multicell inverters topologies controlled, respectively, by PI and FLC controllers are presented in the Sect. 4. Finally, conclusions and future perspectives are discussed in Sect. 5.

# 2 Structure and control scheme of the multicell inverter fed induction motor drive

The power circuit of the variable-speed induction motor drive considered in this paper is presented in Fig. 1.

#### 2.1 Overview of the multicell converter

The type of converter selected in this paper is the multiserial converter based on the so-called Meynard and Foch structure which results from the connection of N floating voltage sources in series to obtain (N + 1) discrete levels of output voltage, indexed from 0 to N (noted n). The voltage sources are the voltage of the power bus (constant voltage)  $v_{dc}$  and the (N - 1) capacitors used as foating sources.

With the symmetric PWM control, this structure has the following properties: (1) natural stability, (2) minimum number of commutations (only two per cell in a period), (3) low harmonic level, (4) voltage constraints equally distributed on each switch. However, in order to analyse the properties of multicell series converter in steady state, the following assumptions are made to simplify the study: (1) the switches are supposed ideal, (2) the dead-time will be taken equal to zero and (3) the voltage and current sources are assumed ideal.

The general scheme for three-phase multicell converter associated with an induction motor is illustrated in Fig. 2.

The multilevel inverter consists of pairs of semiconductor switches separated by floating capacitors. The two switches in each pair must always be complementary in order to avoid shorting the voltage sources. Each pair of switches represents a switching cell. The principle of this topology is to divide the DC bus voltage into several basic voltage sources. The operation of each switching cell is similar to a two-level inverter with a voltage source equal to  $v_{dc}/N$  (*N* is the number of cells and  $v_{dc}$  is the supply voltage) and a current source. The maximum voltage of the IGBTs switching are achieved by  $V_{max} = v_{dc}/N$ .

The first advantage of these converters is the reduced voltage requirements on the switches. It is necessary to identify all the converter possible states, the voltage across the floating capacitors and the converter's output voltage level for all states (equal to  $jv_{dc}/N$ , j = 1, ..., N). Multicell series converters also improve the waveform of the output voltage and allow greater flexibility for different voltage levels as compared to the NPC structure.

This study focuses on a three-phase five-level multicell inverter topology to highlight the following two results:

**Fig. 1** Power circuit of the multicellular inverter induction motor drive

Fig. 2 Structure of the

motor

connected to the induction

multilevel inverter with N cells



- (i) Increased voltage levels By increasing the level of the structure, the stress on the IGBTs can be reduced, consequently the multicell inverter provides more levels than the NPC or cascade inverter topologies.
- (ii) Increased bandwidth The multicell inverter allows an increase in the harmonics switching frequency [31] in proportion with the number of cells. Hence the harmonics will be shifted farther from the fundamental.

Table 1 gives the different configurations of the multicellular converter (3 cells). These configurations describe the states of the switches and define the control states  $S_k$  as follows:

- (i) State 1, indicates that the upper switch is on.
- (ii) State 0 indicates that the switch is upper switch is open and the bottom on is closed.

In such a structure, the synthesis of the output waveform is much simpler than in the NPC structure. Table 1 shows the states for a four-level (N = 3 cells) multicell series converter. Here, we must recall that switches of a switching cell are controlled in a complementary manner. This gives  $2^N$  possible logic states (in Table 1, we have  $2^3 = 8$  possible states).

In the general case of a N cells multicell structure, the number of output voltage level is N + 1, and the number of capacitors is N - 1 and this structure represent 2N switches.

 Table 1
 States of 4-level inverter and its output voltage

States	<b>S</b> <sub>3</sub>	<b>S</b> <sub>2</sub>	$S_1$	Output voltage	Level
1	0	0	0	0	1
2	0	0	1	$(1/3)v_{\rm dc}$	2
3	0	1	0	$(1/3)v_{\rm dc}$	2
4	0	1	1	$(2/3)v_{\rm dc}$	3
5	1	0	0	$(1/3)v_{\rm dc}$	2
6	1	0	1	$(2/3)v_{\rm dc}$	3
7	1	1	0	$(2/3)v_{\rm dc}$	3
8	1	1	1	$v_{ m dc}$	4

The generalization of this method to the other quantities is summarized in Table 2.

#### 2.2 PSPWM switching control

The PSPWM control is based on a frequency behaviour of the converter. The main idea is to achieve N binary signal with identical phase shift of  $2\pi/N$ . The duty cycle of these signals is calculated in order to adjust the output current in order to control the speed of the induction motor. The switching between modes generates a harmonic in the current. The capacitor voltages are naturally balanced around their baseline values. The PWM control is usually generated

Number of associated cells	Ν
Number of possible states	$2^N$
Number of voltage levels at output	N + 1
Number of floating capacity	N-1
Value of main power supply	$v_{ m dc}$
Value of voltage source of the cell <i>j</i>	$v_{cj} = \frac{j}{N} v_{dc}$
Number of switches	2N

by comparing a triangular and reference signals. In PSPWM, a sinusoidal reference voltage waveform is compared with a triangular carrier signal to generate the gate signals for controlling the switches of multicell-inverter. The PSPWM control method leads to reduced switching losses. Note that it is possible to obtain N different switching cycles.

The control of the multicell inverter is obtained by a PSPWM strategy. When all the cells are controlled with a square wave signal, the following results are obtained:

• With an the same phase shift between adjacent cells, the output voltage uses simply two levels and the harmonics are multiples orders of  $Nf_c$  ( $f_c$  being the switching frequency), then the offset is:

$$\varphi = \frac{2\pi}{N} \tag{1}$$

• With equal amplitude modulation indices *M<sub>i</sub>* in all three phases, the output voltage fundamental of *V<sub>s1</sub>* does not depend on the state of the inverter, but only on the bus voltage and modulation index:

$$V_{s1} = M_i \times v_{\rm dc} \tag{2}$$

For optimal operation, the control signals must have the same phase shift of  $2\pi/N$ . There are several solutions to achieve this and in this paper a simple method is presented.

In the classical PWM, the control signal for each cell is generated by the intersection between a triangular carrier frequency  $f_p$  and the modulating sinusoidal signal of frequency  $f_m$ . The equations to generate triangular signals noted  $t_{rk}$  evolving on the interval [-1,1] are:

$$t_{r1} = \frac{1}{2} \left[ 1 + \frac{2}{\pi} \sin^{-1} \left( \sin \left( 2\pi f_p t - \varphi_1 + \frac{\pi}{2} \right) \right) \right]$$
$$t_{r2} = \frac{1}{2} \left[ 1 + \frac{2}{\pi} \sin^{-1} \left( \sin \left( 2\pi f_p t - \varphi_2 + \frac{\pi}{2} \right) \right) \right]$$

$$t_{r3} = \frac{1}{2} \left[ 1 + \frac{2}{\pi} \sin^{-1} \left( \sin \left( 2\pi f_p t - \varphi_3 + \frac{\pi}{2} \right) \right) \right]$$
  
$$\vdots$$
  
$$t_{rN} = \frac{1}{2} \left[ 1 + \frac{2}{\pi} \sin^{-1} \left( \sin \left( 2\pi f_p t - \varphi_N + \frac{\pi}{2} \right) \right) \right]$$
(3)

By generalizing Eq. (3) yields:

$$t_{rk} = \frac{1}{2} \left[ 1 + \frac{2}{\pi} \sin^{-1} \left( \sin \left( 2\pi f_p t - \varphi_{ik} + \frac{\pi}{2} \right) \right) \right], \quad (4)$$

where

$$\varphi_{ik} = (k-1)\frac{2\pi}{N}$$
 (5) (5)

#### 2.3 Modified PSPWM

In three phase, harmonics can be reduced without reducing the amplitude of the output voltage because the harmonic of order 3 or a multiple of 3 are eliminated from the output voltages. A harmonic of order 3 can be added to a sinusoid of frequency  $f_m$  to form the reference waveform. This harmonic appears in the three fictitious voltages  $V_{ao}$ ,  $V_{b0}$  and  $V_{c0}$  with respect to the fictitious mid-point 0, but does not appear in the phase output voltages  $V_{an}$ ,  $V_{bn}$ ,  $V_{cn}$  and line-to-line output voltages  $V_{ab}$ ,  $V_{bc}$ ,  $V_{ca}$ .

The addition of harmonic of order 3 increases the maximum amplitude of the fundamental in the output voltages.

Figure 3 shows that the reference voltage is composed of two sinusoids one for the fundamental and the other for the harmonic of order 3.

The new reference signal for the modified PSPWM is:

$$(V_a - V_o)_w = \frac{U}{2} \left( M_i \sin\left(\omega t\right) + k \sin\left(3\omega t\right) \right)$$
(6)

This is called sub-optimal control.



Fig. 3 Sub-optimal PSPWM



Fig. 4 PSPWM strategy applied to the multicell inverter. a Classical PSPWM. b Modified PSPWM



Fig. 5 Waveforms of the capacitors voltages, line-to-line output voltage and its harmonic spectrum. a Classical PSPWM. b Modified PSPWM

The maximum value of  $M_i$  occurs for  $k = 1/3\sqrt{3}$  and is found as:

$$M_{i_{\max}} = \frac{2}{\sqrt{3}} \tag{7}$$

Therefore, with sub-optimal control, the maximum amplitude of the fundamental output voltage  $V_1$  corresponding to  $M_{i_{\text{max}}}$  is:  $V_{1,M_{i_{\max}}} = 2/\sqrt{3}V_{dc}$  (8)

The basic principle of the conventional intersective modulation can directly be used to control a cell with series switches (Fig. 4). The classical and modified PSPWM provide the control (variable  $t_{\rm ON}$ ) as shown in Fig. 4 which is illustrated for a switching frequency  $f_p = 600$  Hz.

For example, consider a three-phase inverter with threecells (N = 3) with the following parameters:  $v_{dc} =$ 



induction motor

**Fig. 6** Bloc diagram of IFOC for the multicell inverter-fed

Electr Eng



400 V,  $L_L = 20 \text{ mH}$ ,  $R_L = 0.5 \Omega$ ,  $f_m = 50 \text{ Hz}$ ,  $f_p = 600 \text{ Hz}$ ,  $M_i = 0.8$ .

In steady state, the  $C_1$  and  $C_2$  capacitor voltages reached balanced values of 133.33 V and 266.66 V, respectively, (this is a natural balancing). From the simulation results, the following remarks can be drawn:

- 1. If the control signals of the switching cells have the same modulation index in magnitude and are phase shifted by  $2\pi/N$  (for this simulation N = 3 as shown in Fig. 5) then there is only one open-loop stable state for the distribution capacitors voltages:  $v_{C_j} = \frac{jv_{dc}}{N}$  (avec N = 3) and  $j = 1 \dots (N 1)$ .
- 2. From Fig. 5, the following points can be drawn: the maximum theoretical fundamental voltage is  $\frac{M_i v_{dc} \sqrt{3}}{2} = \frac{0.8 \times 400 \times \sqrt{3}}{2} = 277.1281 V$  W which is close to the value obtained 276.9 V in the simulation. The spectral analysis shows that Fourier harmonics are rejected to the higher order frequency  $N \times f_p = 3 \times 600 = 1800 Hz$  which improves the quality of three-phase currents and facilitates filtering.
- 3. From Fig. 5, the following remarks can be drawn: (1) the instantaneous line-to-line voltage contains three voltage levels in addition to level zero hence four levels in total, (2) the theoretical fundamental peak voltage is  $\frac{M_i v_{dc} \sqrt{3}}{2} = \frac{0.8 \times 400 \times \sqrt{3}}{2} = 277.1281V$  which is close to the value obtained in the simulation, (3) Fourier spectral

analysis has shown that harmonics are rejected towards high frequencies of order  $N \times \frac{f_{\text{swit}}}{f_m} = 3\frac{600}{50} = 36$  (corresponding to a frequency of  $600 \times 3 = 1800$  Hz. This will improve the quality of the three-phase currents and make the filtering of these harmonics easier.

4. The harmonic spectrum of the line-to-line output voltage of phase A of the multicell are shown in Fig. 5. From this figure, the THD is 43.60% for the classical PSPWM and 37.40% for proposed PSPWM. In this case, the group of harmonics can be shifted further away from the fundamental frequency. This leads to a good quality of the currents at the output of the inverter.

## **3** Indirect vector control of the multicell-fed induction motor drive

This method is based on the estimation of the position of the flux vector. The voltages or currents ensuring the orientation of the flux and decoupling are estimated from a dynamic model of the machine. It is important to note that the indirect method is simpler to implement and widely used than the direct method, but the choice between the two methods vary from one application to another. Figure 6 illustrates the principle of the indirect rotor flux oriented control (IFOC) of a variable-speed induction motor drive.

![](_page_6_Figure_2.jpeg)

![](_page_6_Figure_3.jpeg)

Fig. 7 Response of rotor speed, the electromagnetic torque and the stator current of phase A of the motor. a PI controller, b FLC

The IFOC control block generates the three-control variables  $v_{sd}$ ,  $v_{sq}$  and  $\omega_m$ , according to two reference inputs  $(i_{sq}, \varphi_{ref})$  that ensure decoupling. These control quantities generated by the IFOC block are used to adjust the direct  $i_{sd}$  and quadratic  $i_{sq}$  components of the stator currents to their reference values, and therefore the flux and torque are maintained at their reference values. In our case, the voltages or currents provide the direction of the flux and the decoupling. An electrical model of the machine is required to develop the algorithms necessary for defining  $v_{sd}$  and  $v_{sq}$  control variables.

The strategy of indirect vector control of the induction motor was based on a classical PI control designed using a pole placement technique. The stator flux is maintained at its rated value ( $\varphi_{sn}$ ) for the system to operate in the range of the base speed. For speeds higher than the base speed, the flux cannot be maintained constant; it must be reduced to limit the voltage at the machine terminals. Under these conditions, the reference flux is defined by:

$$\varphi_{\text{sref}} = \begin{cases} \varphi_n & \text{if } |\Omega_r| \le \Omega_n \\ \frac{\Omega_n}{|\Omega_n|} \varphi_n & \text{if } |\Omega_r| > \Omega_n \end{cases}$$
(9)

The design of indirect field control for a multicell inverter is similar to the classical 2 level inverter.

The speed controller is used to define the electromagnetic torque reference. With indirect vector control, the induction motor voltages  $v_{sd}$  and  $v_{sq}$  in steady-state are given by:

$$\begin{cases} v_{\rm sd} = R_s i_{\rm sd} - \omega_s L_s \sigma i_{\rm sq} \\ v_{\rm sq} = \omega_s L_s i_{\rm sd} + R_s i_{\rm sq} \end{cases}$$
(10)

with  $\sigma$  being the dispersion constant of Blondel defined as

$$\sigma = 1 - \frac{L_m^2}{L_r L_s} \tag{11}$$

The current of d axis is obtained from the reference flux and is given by:

$$i_{\rm sd} = \frac{\varphi_{\rm ref}}{L_m} \tag{12}$$

The inverse Park transformation block is defined by the following matrix:

$$P^{-1}(\theta_{s}) = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_{s}) & -\sin(\theta_{s}) & \frac{1}{\sqrt{2}} \\ \cos(\theta_{s} - 2\frac{\pi}{3}) & -\sin(\theta_{s} - 2\frac{\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta_{s} - 4\frac{\pi}{3}) & -\sin(\theta_{s} - 4\frac{\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix}$$
(13)

where  $\theta_s = \int \omega_s dt$ 

#### **4** Simulation results

The models for classical and multicellular inverter topologies with IFOC strategy based on the technique of SPWM, classical and modified PSPMW have been developed and implemented using Matlab/Simulink SimPowerSystems toolbox. The proposed circuit model consist of a three-phase power source, the multilevel inverter and the induction motor with IFOC strategy.

Electr Eng

![](_page_7_Figure_3.jpeg)

Fig. 8 Responses of rotor speed, the electromagnetic torque and the stator current of the phase A of motor with a change of reference speed by  $\pm 150$  rad/s. **a** PI controller, **b** FLC

The main objective of this simulation study was to analyse and compare the performance of the multicell-inverter and a conventional two-level inverter with respect to torque ripples. Different simulation scenarios are presented to evaluate the performance of the two different controllers.

#### 4.1 Transient and steady-state performance

Figures 7 and 8 show the responses of the speed, the electromagnetic torque and the stator current of phase A of the induction motor. The load torque of  $\pm 10$  N was applied. Both controllers gave satisfactory transient and steady-state tracking responses There is a small overshoot in the response produced by the PI controller.

### 4.2 Quality of the current and torque ripples minimization

Electric power quality has become an important issue in recent years within the scientific and industrial communities. This concept determines the parameters that define the properties of electricity produced in normal conditions, in terms of continuity of supply and voltage characteristics (symmetry, frequency, amplitude, waveform).

Some electric equipment are considered as non-linear loads because they generate current harmonics with frequencies that are integer multiples of the fundamental frequency, or sometimes arbitrary frequencies. These harmonic currents can result in harmonic voltages at the connection

points which may pollute consumers appliances connected to the same network. These harmonics also cause overload of the transmission lines, unwanted tripping, accelerated aging and performance degradation of the distribution system equipment. Consequently, it necessary to reduce dominant harmonics below 5% as specified in the IEEE harmonic standards [24].

Figure 9 shows the responses of the rotor speed, the electromagnetic torque and the stator current of phase A of the induction motor with the conventional two-level and multicell three-level inverters. The same load torque of  $\pm 10$  N is applied to the induction motor. A significant reduction of the torque ripples has been achieved with the three-level multicell inverter as compared with the two-level inverter.

The harmonic spectra of the current of phase A of the motor are shown in Fig. 10 for the classical and multicell inverters. The THD is 5.12% for the classical inverter and 4.44% for three-level multicell inverter.

Figure 11 shows the response of the rotor speed, the electromagnetic torque and the stator current of phase A of the induction motor for three-, four- and five-level multicell inverter. The torque disturbance  $\pm 10$  N was applied. There is a considerable reduction in the torque ripples as the number of cell is increased. These results clearly demonstrate that the five-level multicell inverter gives improved transient response and better quality of the output currents.

![](_page_8_Figure_2.jpeg)

![](_page_8_Figure_3.jpeg)

Fig. 9 Responses of rotor speed, the electromagnetic torque and the stator current of phase A of the motor: **a** classical inverter, **b** multicell inverter N = 2 (three level)

![](_page_8_Figure_5.jpeg)

Fig. 10 Waveform of the stator current of phase A and harmonic spectrum. a Classical two-level inverter. b Multicell three-level inverter

![](_page_9_Figure_3.jpeg)

Fig. 11 Reponses of the rotor speed, electromagnetic torque and stator current the phase for the multicell inverter:  $\mathbf{a}$  three levels,  $\mathbf{b}$  four levels,  $\mathbf{c}$  five levels

![](_page_9_Figure_5.jpeg)

Fig. 12 Waveform of motor current of phase A and harmonic spectrum with the multicell inverter based on PSPWM: **a** three levels, **b** four levels, **c** five levels

The harmonic spectrum of the stator current of phase A of the motor with the three-, four- and five-level multicell inverters, respectively, are shown in Fig. 10.

The IEEE standards [24] are used to compare the performance of the three inverter topologies with respect to the quality of the output currents and the reduction of torque ripples. From Figs. 12 and 13 the following can be noted: (1) the five-level multicell inverter produced the lowest THD as compared to the other converters; (2) the proposed PSPWM technique leads to the lowest THD compared to classical strategy PSPWM; (3) the five-level topology produced the lowest torque ripples and rejected harmonics towards the high frequencies.

![](_page_10_Figure_2.jpeg)

![](_page_10_Figure_3.jpeg)

Fig. 13 Waveform of motor current of phase A and harmonic spectrum with the multicell inverter based on the modified PSPWM: a three levels, **b** four levels, **c** five levels

![](_page_10_Figure_5.jpeg)

Fig. 14 Waveforms of the terminal voltage and capacitors voltages: a three levels, b four levels, c five levels

0.5

1

Time (s)

1.5

2

0.5

1

Time (s)

2

1.5

1

Time (s)

0.5

1.5

2

Electr Eng

![](_page_11_Figure_3.jpeg)

Fig. 15 Line-to-line output voltage and harmonic spectrum with the multicell inverter based on PSPWM: a three levels, b four levels, c five levels

![](_page_11_Figure_5.jpeg)

Fig. 16 Line-to-line output voltage and harmonic spectrum with the multicell inverter based on the modified PSPWM: a three levels, b four levels, c five levels

Table 3 summarizes the results and comparative performance of the inverter topologies and PWM strategies.

Figure 14 shows the DC bus voltage  $v_{dc}$  which reaches a steady-state value of 590 V after a time of 0.2 s, the floating capacitors voltages have an average value of 295 V for N = 2, 196.66 and 293.33V for N = 3 and then 147.5, 295, 442.5 V for N = 4.

The harmonic spectrum of the line-to-line output voltage of phase A of the multicell are shown in Figs. 15 and 16 for the three, four and five levels, respectively, for the classical and modified PSPWM strategies. From Figs. 15 and 16 the following can be noted:

- (i) The five-level multicell inverter produced the lowest THD as compared to the other converters
- (ii) The proposed PSPWM technique leads to the lowest THD compared to classical strategy PSPWM
- (iii) The five-level topology produced the lowest torque ripples and rejected harmonics towards the high frequencies. In this case, the group of harmonics can be shifted further away from the fundamental frequency. This leads to a good quality of the currents at the output of the inverter.

![](_page_12_Picture_0.jpeg)

#### **5** Conclusion

In this paper, a comprehensive simulation study of the induction motor based on the multicell-inverter topologies was presented with different control strategies to improve the quality of the current and minimize torque ripples.

The indirect field-oriented structure was used with the orientation of coordinate system (d, q) on the rotor to decouple the torque and flux variables. The control signals of the multicell inverter switches are achieved by a phase-shifted PWM (PSPWM) technique. The simulation results showed an enhanced performance of the induction motor transient speed response with a substantial reduction in the electromagnetic torque ripples of the induction motor. The total harmonic distortion (THD) of the stator currents of the induction motor has been reduced to 0.99% for the fivelevel multicell-inverter as compared to the classical inverter where the THD was 5.758% with a 1.05 kHz switching frequency. The simulation results also showed improved transient response characteristics of the motor speed with reduced ripples using the fuzzy logic controller based on the five-level multicell-inverter.

#### Appendix A

The parameters and values used in the simulation model are listed in Tables 4, 5, 6.

Induction motor	
Rated power, $P_{,n}[kW]$	2
Rated frequency, $f_{,n}$ [Hz]	50
Stator resistance, $R_{\rm s}$ [ $\Omega$ ]	4.850
Stator leakage inductance, $L_{ls}$ [mH]	16
Rotor resistance, $R_r [\Omega]$	3.805
Rotor leakage inductance, $L_{lr}$ [mH]	16
Mutual inductance, L <sub>m</sub> [mH]	258
Inertia, $J$ [kg m <sup>-2</sup> ]	0.031
Viscous friction coefficient, $f [Nmsrad^{-1}]$	0.00114
Number of pole pairs, p	2

Table 5	Parameters	of multicell-inverter	
---------	------------	-----------------------	--

Capacity, C [µF]	5000
Switching frequency [kHz]	3

#### Table 6 Parameters of indirect vector control IFOC

IFOC control block

Proportional gain speed controller, $K_{p\Omega}$	1
Integral gain speed controller, $K_{i\Omega}$	15.872

![](_page_12_Figure_14.jpeg)

Fig. 17 Equivalent circuit of induction motor

## **Appendix B: Dynamic model and IFOC strategy of the induction motor**

The equivalent circuit of the induction motor is shown in Fig. 17.

The relationships in the stator and rotor of the induction motor of Fig. (written in the Park system are:

Stator:

$$v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq}$$
  

$$v_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd}$$
(14)

where  $v_{sd}$ ,  $v_{sq}$  are the stator voltage components in the Park system,  $\omega_s$  is the synchronous speed of the generator, and  $\varphi_{sd}$ ,  $\varphi_{sq}$  and  $i_{sd}$ ,  $i_{sq}$  are, respectively, the flux and stator current components in *d* and *q* axis of the Park frame.

The fluxes are given by:

$$\begin{cases} \varphi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \varphi_{sq} = L_s i_{sq} + L_m i_{rq} \end{cases}$$
(15)

Rotor:

$$\begin{cases} v_{rd} = 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \\ v_{rq} = 0 = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \end{cases}$$
(16)

The rotor voltages  $v_{rd}$  and  $v_{rq}$  are set to zero since the rotor is short-circuited,  $\omega_r$  is the rotor speed of the generator, and  $\varphi_{rd}$ ,  $\varphi_{rq}$  and  $i_{rd}$ ,  $i_{rq}$  are, respectively, the flux and rotor current components in *d* and *q* axis of the Park frame.

![](_page_13_Figure_3.jpeg)

Fig. 18 Scheme of the FLC controller

The fluxes are given by:

$$\begin{cases} \varphi_{rd} = L_m i_{sd} + L_r i_{rd} \\ \varphi_{rq} = L_m i_{sq} + L_r i_{rq} \end{cases}$$
(17)

The dynamic model of an induction machine is described by the following equations written in the dq synchronous reference frame:

$$\begin{cases} \frac{di_{sd}}{dt} = -\left(\frac{1}{T_s\sigma} + \frac{(1-\sigma)}{T_r\sigma}\right)i_{sd} \\ +\omega_s i_{sq} + \frac{(1-\sigma)}{T_r L_m\sigma}\varphi_{rd} + \frac{(1-\sigma)}{L_m\sigma}\omega_r\varphi_{rq} + \frac{1}{L_s\sigma}v_{sd} \\ \frac{di_{sq}}{dt} = -\omega_s i_{sd} - \left(\frac{1}{T_s\sigma}\right)i_{sq} - \frac{(1-\sigma)}{L_m\sigma}\omega_r\varphi_{rd} + \frac{(1-\sigma)}{T_r L_m\sigma}\varphi_{rq} + \frac{1}{L_s\sigma}v_{sq} \\ + \frac{(1-\sigma)}{T_r\sigma}\right)i_{sq} - \frac{(1-\sigma)}{L_m\sigma}\omega_r\varphi_{rd} + \frac{(1-\sigma)}{T_r}\varphi_{rd} + \omega_{slip}\varphi_{rq} \\ \frac{d\varphi_{rq}}{dt} = \frac{L_m}{T_r}i_{sd} - \frac{1}{T_r}\varphi_{rd} + \omega_{slip}\varphi_{rq} \\ \frac{d\varphi_{rq}}{dt} = \frac{L_m}{T_r}i_{sq} - \omega_{slip}\varphi_{rd} - \frac{1}{T_r}\varphi_{rq} \\ T_{em} = p\frac{3}{2}\frac{L_m}{L_r}\left(\varphi_{rd}i_{sq} - \varphi_{rq}i_{sd}\right) \\ T_{em} - T_r = J\frac{d\Omega_r}{dt} + f\Omega_r, \end{cases}$$
(18)

where  $\omega_r = p\Omega_r$ ;  $\omega_{\text{slip}} = [\omega_s - \omega_r]$ ;  $T_r = \frac{L_r}{R_r}$ ;  $T_s = \frac{L_s}{R_s}$ With  $\sigma$  is the coefficient of dispersion and is given by

$$\sigma = 1 - \frac{L_m^2}{L_s L_r},\tag{19}$$

where  $T_{em}$  is the electromagnetic torque [Nm] and  $T_m$  denotes the mechanical torque produced by the load [Nm].

The major aim of the vector control of induction motors is, as in DC machines, to separately control the torque and the flux; this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector [32] as shown in Fig. 1, the *d* axis is aligned with the rotor flux space vector. Under this condition we have:

 $\varphi_{rq} = 0$  and  $\varphi_{rd} = \varphi_r$ 

Thus, the dynamic equations (18) yield:

$$\begin{cases}
v_{sd} = R_s i_{sd} - \omega_s L_s \sigma i_{sq} \\
v_{sq} = \omega_s L_s i_{sd} + R_s i_{sq} \\
\varphi_r = L_m i_{sd} \Rightarrow i_{sd} = \frac{\varphi_r}{L_m} \\
\omega_{slip} = \frac{L_m}{T_r} \frac{i_{sq}}{\varphi_r} \\
T_{em} = p_2^3 \frac{L_m}{L_r} \varphi_r di_{sq} \\
T_{em} - T_r = J \frac{d\Omega_r}{dt} + f \Omega_r
\end{cases}$$
(20)

#### Appendix C: Design of the PI and FLC controllers

#### 5.1 PI controller

Speed controller can determine the electromagnetic torque reference in order to maintain the same speed. The speed can be controlled using a PI controller.

The transfer function of the mechanical speed of the induction motor is given by

$$\frac{\Omega_r}{T_{\rm em}} = \frac{1}{Js+f} = \frac{G_\Omega}{s+p_\Omega},\tag{21}$$

where  $G_{\Omega} = \frac{1}{J}$  and  $p_{\Omega} = \frac{f}{J}$  are, respectively, the static gain and the pole of the transfer function of the mechanical speed of the asynchronous generator.

The closed-loop transfer function is

$$T_{\rm CL}(s) = \frac{G_{\Omega} \left[ K_{p_{\Omega}} s + K_{i_{\Omega}} \right]}{s^2 + \left[ G_{\Omega} K_{p_{\Omega}} + p_{\Omega} \right] s + G_{\Omega} K_{i_{\Omega}}}$$
(22)

The controller parameters can be determined using pole placement. Let the desired closed-loop poles be

$$s_{1,2} = -\sigma_c \pm j\omega_n \sqrt{1 - \xi^2} = \gamma \ (-1 \pm j) \tag{23}$$

The poles are selected to improve the closed-loop response by three-fold with regard to the open-loop system. Solving for the PI controller's parameter [33]

$$\begin{bmatrix} K_{p_{\Omega}} = \frac{2\gamma - p_{\Omega}}{G_{\Omega}} \\ K_{i_{\Omega}} = \frac{2\gamma^2}{G_{\Omega}} = 2\gamma^2 J \end{bmatrix}$$
(24)

#### 5.2 FLC controller

The following structure shows the diagram of an FLC controller (Fig. 18):

The input variables are the error and its derivative

$$\begin{cases} e(k) = \omega_{\text{ref}} - \omega_m \\ \Delta e(k) = e(k) - e(k-1) \end{cases}$$
(25)

The input and output universe of discourse are normalized [-1.1]. Thus there should be adaptation gains for the desired dynamics, but there is no systematic technique for the determination of these gains, and hence a trial and error procedure is used. The selected membership functions have a trapezoidal and triangular ends in the universe of discourse (Fig. 19).

The defuzzification is based on the centre of gravity method. For the membership functions were chosen for each variable triangular and trapezoidal shape as shown in Fig. 19. where

![](_page_14_Picture_0.jpeg)

![](_page_14_Figure_4.jpeg)

Table 7 FLC rules

$\Delta e$	e						
	GN	PN	Z	PP	GP		
GN	GN	GN	GN	PN	Ζ		
PN	GN	GN	PN	Z	PP		
Е	GN	PN	Z	PP	GP		
PP	PN	Z	PP	GP	GP		
GP	Е	PP	GP	GP	GP		

NB = Negative Big, NS = Negative Small, Z = Approximately zero, PS = Positive Small, PB = Positive Big (Table 7).

Fuzzy command manipulates language knowledge and has a wealth of options for the shape of the membership functions, the type of fuzzification and defuzzification and type inference.

#### **Appendix D: Modelling of the multicellular inverter** by *N*-cells

The *N*-cell instantaneous model connected in series (Fig. 20) is presented in the following.

The setting in equation of this connection considers local variations in the voltage of each floating capacitor. These variations depend on the output current *i* and the difference between the duty cycles of the adjacent switching cells (k, k -1) in each capacitor k.

$$\frac{\mathrm{d}v_{C_1}(t)}{\mathrm{d}t} = \frac{i_L(t)}{C} \left(S_2 - S_1\right) \tag{26}$$

$$\frac{\mathrm{d}v_{C_k}(t)}{\mathrm{d}t} = \frac{i_L(t)}{C} \left(S_{k+1} - S_k\right)$$
(27)

$$\frac{\mathrm{d}v_{C_{n-1}}(t)}{\mathrm{d}t} = \frac{i_L(t)}{C} \left(S_{k+1} - S_k\right)$$
(28)

The representation of this model in a matrix form is presented below.

$$\frac{d}{dt}\begin{pmatrix} v_{C_{1}}(t)\\ v_{C_{2}}(t)\\ v_{C_{3}}(t)\\ \vdots\\ v_{C_{n-1}}(t) \end{pmatrix} = \frac{1}{C}\begin{pmatrix} -i_{L}(t) & i_{L}(t) & 0 & \dots & 0\\ 0 & -i_{L}(t) & i_{L}(t) & \dots & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & 0 & \dots & -i_{L}(t) & i_{L}(t) \end{pmatrix}$$

$$\begin{pmatrix} S_{1}\\ S_{2}\\ S_{3}\\ \vdots\\ S_{N} \end{pmatrix}$$
(29)

To ensure normal operation, it is indispensable to make certain a balanced distribution of the floating voltages  $v_{Cj,k} = kv_{dc}/N$  (where j=abc corresponding the three phase). The *N*-cell output voltage  $v_{Cj,k}$  can be determined by:  $\left(\frac{v_{dc}}{N}, \ldots, (N-1)\frac{v_{dc}}{N}, v_{dc}\right)$ 

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} v_{AM} \\ v_{BM} \\ v_{CM} \end{bmatrix}$$
(30)

With:

$$\begin{cases} v_{aO} = v_{sa} - \frac{v_{dc}}{2} \\ v_{bO} = v_{sb} - \frac{v_{dc}}{2} \\ v_{cO} = v_{sc} - \frac{v_{dc}}{2} \end{cases}$$
(31)

The output voltage  $v_{si}$  corresponds to the addition of terminal voltages of the switches.

$$v_{s_i} = \sum_{k=1}^{N} v_{j,k} = \sum_{k=1}^{N} S_{j,k} \left( v_{Cj,k} - v_{Cj,k-1} \right)$$
(32)

سفارش ترجمه این مقاله http://www.itrans24.com/landing1.html تماس: (۲۱) ۶۶۵۷۲۲۳۸–۲۰

Electr Eng

Fig. 20 General structure of a single arm of a multicell inverter

![](_page_15_Figure_4.jpeg)

through:  $v_{C_{j,N}} = \frac{v_{dc}}{2}$  and  $v_{C_{j,0}} = 0$ So

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} \sum_{k=1}^{N} S_{a,k} \left( v_{Ca,k} - v_{Ca,k-1} \right) \\ \sum_{k=1}^{N} S_{b,k} \left( v_{Cb,k} - v_{Cb,k-1} \right) \\ \sum_{k=1}^{N} S_{jc,k} \left( v_{Cc,k} - v_{Cc,k-1} \right) \end{bmatrix}$$
(33)

The variations of the floating voltages  $v_{Cj,k}$  are a function of the current  $i_L$ , which in turn depends on the state of the adjacent cells  $\operatorname{Cel}_{j,k+1}$ ,  $\operatorname{Cel}_{j,k}$  and the load current  $i_L$ . The current  $i_{Cj}$  is a function of the control signals of switches  $S_{j,k+1}$  and  $S_{j,K}$ .

#### References

- Alkorta P, Barambones O, Garrido AJ, Garrido I (2007) SVPWM variable structure control of induction motor drives. IEEE Int Symp Ind Electron 1195–1200
- Mezouar A, Fellah MK, Hadjeri S, O. Touhami, Y. Sahalim (2006) Robust direct field oriented control of induction motors using adaptive observer, IEEE ISIE 2006, July 9–12, 2006, Montreal. Quebec
- Maiti S, Chakraborty C, Sengupta S (2009) Simulation studies on model reference adaptive controller based speed estimation technique for the vector controlled permanent magnet synchronous motor drive, Elsevier. Simul Model Pract Theory 17:585–596
- Adamidis G, Koutsogiannis Z, Vagdatis P (2011) Investigation of the performance of a variable-speed drive using direct torque control with space vector modulation. Electr Power Compon Syst 39:1227–1243
- Takahashi I, Noguchi T (1986) A new quick-response and high efficiency control strategy of an induction motor. IEEE Trans Ind Appl 22(5):820–7
- Habetler TG, Profumo F, Pastorelli M, Tolbert Leon M (1992) Direct torque control of induction machines using space vector modulation. IEEE Trans Ind Appl 28(5):1045–1053
- 7. Depenbrock M (1988) Direct self-control of inverter fed induction machine. IEEE Trans Power Electron 3(4):420–429
- Habebtler TG, Divan DM (1991) Control strategies for direct torque control of induction machines using discrete pulse modulation. IEEE Trans Ind Appl 27(5):893–901
- Senthil U, Fernandes BG (2003) Hybrid space vector pulse width modulation based direct torque controlled induction motor drive. Conf IEEE. PESC'03 3: 1112–1117

- Meynard TA, Foch H (1992) Multi-Level choppers for high voltage applications. EPE J 2(1):45–51
- Meynard T, Foch H, Forest F, Turpin C, Richardeau F, Delmas L, Gateau G, Lefeuvre E(2002) Multicell converters: Derived topologies. IEEE Trans Ind Electron 49(5):978–987 (Special Issue on Multilevel converters, October 2002)
- Gandomi A Ashraf, Varesi K, Hosseini S Hossein (2015) Control strategy applied on double flying capacitor multi-cell inverter for increasing number of generated voltage levels. IET Power Electron 8(6):887–897
- Babaei E, Alilu S, Laali S (2014) A new general topology for cascaded multilevel inverters with reduced number of components based on developed H-bridge. IEEE Trans Ind Electron 61:3932– 3939
- Gupta KK, Jain S (2014) A novel multilevel inverter based on switched DC sources. IEEE Trans Ind Electron 61:3269–3278
- Sadigh AK, Hosseini SH, Sabahi M, Gharehpetian GB (2010) Double flying capacitor multicell converter based on modified phase-shifted pulsewidth modulation. IEEE Trans Power Electron 25:1517–1526
- 16. Dargahi V, Abarzadeh M, KhoshkbarSadigh A, Dargahi S (2014) Elimination of DC voltage sources and reduction of power switches voltage stress in stacked multicell converters: analysis, modeling, and implementation. Int Trans Electr Energy Syst 24(5):653–676
- Dargahi V, Sadigh AK, Abarzadeh M, Pahlavani MRA, Shoulaie A (2012) flying capacitors reduction in an improved double flying capacitor multicell converter controlled by a modified modulation method. IEEE Trans Power Electron 27:3875–3887
- Sadigh AK, Dargahi V, Abarzadeh M, Dargahi S (2014) Reduced DC voltage source flying capacitor multicell multilevel inverter: analysis and implementation. IET Power Electron 7:439–450
- Ajami A, Oskuee MRJ, Mokhberdoran A, Van den Bossche A (2014) Developed cascaded multilevel inverter topology to minimise the number of circuit devices and voltage stresses of switches. IET Power Electron 7:459–466
- Kai-Ming T, Wai-Lok C (2014) Multi-level multi-output singlephase active rectifier using cascaded H-bridge converter. IET Power Electron 7:784–794
- Ajami A, Shokri H, Mokhberdoran A (2014) Parallel switch-based chopper circuit for DC capacitor voltage balancing in diodeclamped multilevel inverter. IET Power Electron 7:503–514
- 22. Marchesoni M, Tenca P (2002) Diode-clamped multilevel converters: a practicable way to balance DC-link voltages. IEEE Trans Ind Electron 49:752–765
- Adam GP, Williams BW (2014) New emerging voltage source converter for high-voltage application: hybrid multilevel converter with dc side H-bridge chain links. IET Gener Transm Distrib 8:765– 773
- Zha X, Xiong L, Gong J, Liu F (2014) Cascaded multilevel converter for medium-voltage motor drive capable of regenerating with part of cells. IET Power Electron 7:1313–1320
- 25. Adil E, Hassan M, Abderrahim B, Ahmed A, Yassine Z, Mohamed A (2015) Real time implementation of sliding mode control for

er fed induction with de 29 773 induction motor drives using dSPACE. Int Rev Electr Eng (IREE) 10(1):36–41

- Mohamed Y, Latha S (2014) Comparative analysis of multicarrier PWM based multilevel Z-source inverter fed induction motor drives with dtc for different modulation indexes. Int Rev Electr Eng (IREE) 9(3):500–505
- 27. Edwin Deepak FX, Rajasekaran V, Ranjitha R (2014) FPGA Implementation of Z-source multilevel inverter fed induction motor drives. Int Rev Electr Eng (IREE) 9(4):735–742
- Tejavathu R, Anup Kumar P (2013) High performance direct torque and flux control of induction motor drive using fuzzy logic based speed controller. Int Rev Electr Eng (IREE) 8(2):696–710
- Ponnambalam P, Praveenkumar M, Krishnamurthy K (2014) MPC for reduced voltage source multicell converter. Int Rev Electr Eng (IREE) 9(3):493–499

- Boulouiha H Merabet, Allali A, Laouer M, Tahri A, Denaï M, Draou A (2015) Direct torque control of multilevel SVPWM inverter in variable speed SCIG-based wind energy conversion system. Renew Energy 80:140–152
- Meynardet T, Foch H (1995) Multilevel converters and derived topologies for high power conversion. In: Proc. IEEE IECON, vol 1, pp 21–26
- Lorenz RD, Lawson DB (1990) A simplified approach to continuous on-line tuning of field-oriented induction machine drives. IEEE Trans Ind Appl 26(3):420–424
- 33. Merabet Boulouiha H, Allali A, Tahri A, Draou A, Denaï M (2012) A simple maximum power point tracking based control strategy applied to a variable speed squirrel cage induction generator. J Renew Sustain Energy 4(053124):3124–3140