BOOSTING THE INDUCTION MOTOR WITH THE TECHNIQUE OF DISCRETE FREQUENCY CONTROL

REBHI Bechir, **LAABIDI Mabrouka**,
University of Tunis El Manar, ENIT, LSE. BP. 37, 1002, Tunis le Belvédère-Tunisie
E-mail: Mabrouka_abidi@yahoo.fr
bechirrebhi@yahoo.fr

ELLEUCH Mohamed
University of Tunis El Manar, ENIT, LSE. BP. 37, 1002, Tunis le Belvédère-Tunisie
melleuch2005@yahoo.fr

Nomenclature

f_n : Line supply frequency
ω_n : Angular velocity
f_o : The new fundamental generated frequency f_o
α_B: The initial lagging phase angle of phase B
α_b, α_c: initial phase angles of the generated voltage.
$n_z = 2r\, n_z$: The number of zero crossing of the generated frequency at 50 Hz.
C_{acc} : The average accelerator torque
I_{sB} : Starting current with Booster technique.
T_s : The starting torque.
I_s : Stator starting current.
C_{DFC} : The average of electromagnetic starting torque developed by induction motor with the DFC
$C_{Booster}$: The average of starting torque developed by the Booster strategy
C_{em} : Electromagnetic torque
C_l : load torque
A,B,C,a,b,c: subscripts denoting phases A,B and C

Abstract: *This paper presents a new control strategy for induction motor starting based on discrete frequency control (DFC). Considering the inversely proportional relation between the motor electromagnetic torque and the power supply frequency, the DFC technique is based on generating voltage waveforms of the sub frequencies of the power supply frequency. The generated voltages with low frequencies are analyzed by the symmetrical components method. The waveform voltage with the best positive sequence is selected. The proposed control strategy performances are simulated using the software PSIM, and experimentally verified on a laboratory machine. With respect to the classical Booster technique, the proposed new strategy leads to a significantly reduced starting current and an improved starting electromagnetic torque.*

Keywords: *Discrete frequency control, Soft Starter, harmonic frequencies, symmetrical components, induction motor, inverter.*

1. Introduction

For many decades, start up of induction motors has occupied a major part of engineering research on machine start up performance [1]-[3]. Among the mostly common stat up techniques, we mention star-delta starting, rotor resistance starting and soft starting Each technique has advantages as well as drawback [4]-[5]. The soft starting technique is used in many industrial applications for induction motor start up. This technique is based on the control of the voltage at constant frequency using AC thyristors for voltage monitoring. The applied voltage is reduced, then slowly increased until the rated voltage is reached [6]. One of the demerits of this strategy is that a small reduction of voltage produces a drop in the machine electromagnetic torque. Considering the quadratic relationship between voltage and electromagnetic torque, this may cause a failure in the start up of the loaded motor. Consequently the starting current, the torque pulsation and the starting torque are decreased, the latter effect being the major drawback of this approach [7]-[9].

The direct on line (DOL) starting strategy is based on utilizing the full line voltage for a short time period at start up as a Booster technique. Then, a soft starter is used until rated speed is reached. Although, allowing a high starting torque, the DOL starting is characterized by a high inrush current, ranging from 4 to 10 times the rated current, and by a high torque pulsation. Therefore, frequent DOL starting may cause undesirable damage and thermal stress of motor winding insulations. For these reasons many methods are being developed in order to improve the starting performance of the induction motor, mainly for reducing the inrush current [10]-[13]. Referring to the basic equation relating the machine electromagnetic torque Cem, the load torque Cr to the machine rotor speed:

$$C_{em} - C_r = J\frac{d\Omega}{dt} \quad (1)$$

It is clear that, as industrial applications are characterized by large start up load torques, the use of the soft starter technique is still limited.

To overcome this problem, the technique of Booster may be used for the first starting time periods, usually between 100 and 200 ms, then followed by the soft starter mode as indicated in Fig 1. The main principle of the Booster technique is to apply the full voltage for the first starting time period in order to develop a high starting torque, until reaching 14% to 20% of rated speed [5]. However this approach offers absolutely no control capability and is characterized by high inrush current and torque pulsation.

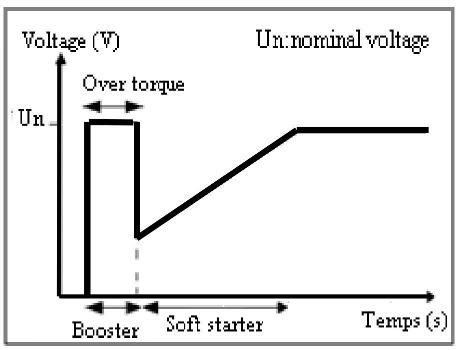


Fig. 1. Startup of induction motor with Booster technique associated to Soft Starter

In this paper, we address these recurrent problems by presenting a new control strategy. The proposed strategy is based on direct frequency control (DFC), instead of the Booster technique. Earlier works on DFC technique associated with induction motors have been reported in [1] and [6]. As a recent work, the authors in [14] have proposed a low cost converter as an interesting application of DFC technique to feed a three phase motor with a single phase supply voltage. The work presented in [3] proposed a fault tolerant operation in adjustable-speed drives and soft starters for induction motors. This alternative is based on start up the induction motor with DFC for the first time period (100-200ms), being followed by soft starting mode. Consequently, the motor can start up with reduced inrush current and high starting torque which is highly requested for repetitive start up. The suggested strategy of DFC allows the use of the main classic inverter (soft starter) as a frequency converter at first, then as a classic soft starter mode. Fig.2 displays the principle of this technique. Performances of the DFC technique used in several applications have been reported in previous works [15-17]. In [15], an example of electrical braking of induction motor has been presented using different methods. The braking mode based on DFC technique confirmed its superiority to conventional techniques [15]. In addition, the DFC technique has been tested for large motors where the motor model includes saturation and skin effects [17].

In [16], a comparative study between three starting strategies has been thoroughly presented: the sophisticated converter, the conventional soft starter and the DFC starter. In the latter work, the DFC technique has been used during start up, and the full voltage has been applied when the motor reaches half rated speed. The main results have shown that the DFC technique gives a trade off between performances and low cost when compared to both the sophisticated converter and the conventional soft starter [16]. It should be noted that the DFC technique leads to an important ripple torque during start up, which may be unaccepted for specific applications. The work presented in this paper attempts to overcome these drawbacks. We propose to reduce the duration of the DFC technique to a shorter time, about 100 ms. This is achieved by applying the DFC technique for first time periods, then associating to a conventional AC ASR controller (Fig.2.b).

This paper is organized in three main sections. The first exposes the DFC theory where starting control rules related to 7.14 Hz, 12.5 Hz, 16.66 Hz and 25 Hz are determined. The second part presents the relevant simulation results. Finally, the experimental tests are exposed and analyzed.

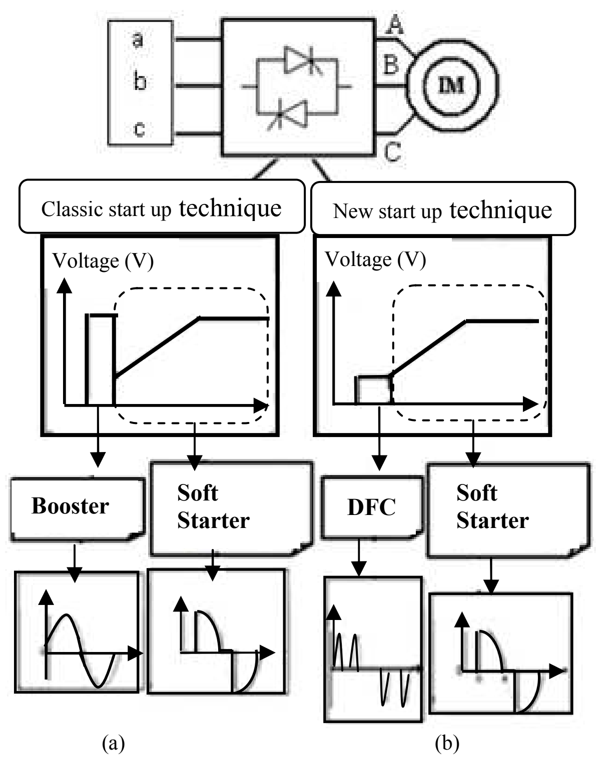


Fig. 2. Induction motor starting strategies: (a) classic starting or Booster associated to soft starter, (b) New proposed technique: DFC associated to soft starter

2. The Discrete Frequency Control

The main principle of the DFC technique is to generate discrete frequencies which are sub harmonics of the ac power supply frequency. This is done by omitting or including selected half cycles of the line voltage. AC thyristor controllers are used as inverter [6],[19] to the generate voltage waveforms at sub-multiples of the line frequency, to improve starting electromagnetic torque of the induction motors with a significantly reduced current. Fig.3 shows half cycle voltages used for generating sub-multiple frequencies based on a 50 Hz power supply: 12.5 Hz, 16.66 Hz and 25 Hz.

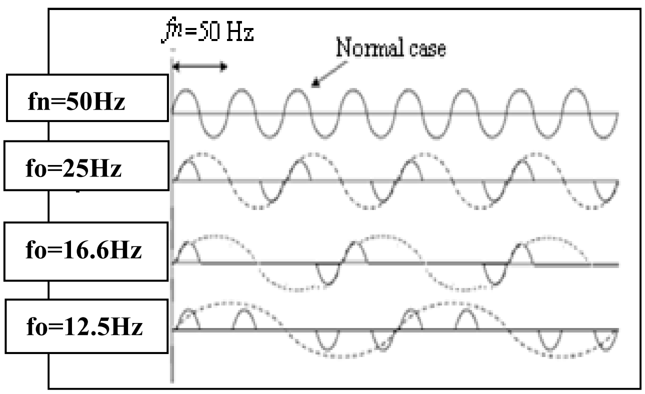


Fig. 3. Sub-multiples of the line frequency: 12.5 Hz, 16.66 Hz, 25 Hz.

Considering a the three-phase balanced power supply with nominal frequency $f_n = 50$ Hz, the three-phase voltages u_a, u_b, u_c, are given by:

$$u_a = u_m \sin(\omega_n t)$$
$$u_b = u_m \sin\left(\omega_n t - \frac{2\pi}{3}\right) \quad (2)$$
$$u_c = u_m \sin\left(\omega_n t - \frac{4\pi}{3}\right)$$

Where $\omega_n = 2\pi f_n$.

Sub-multiple pulsations related to the frequency f_o are:

$$\omega_o = 2\pi f_o = \frac{\omega_n}{r} \quad (3)$$

Where r is a non zero positive integer. It is assumed that the initial phase of the new generated voltage applied to the induction motor phase a is the same as that of the power supply voltage phase A [1]. The generation of positive phase sequences implies that there is a 120-degree phase shift between phases for the three-phase balanced system. Taking phase A as the reference, the phase shift between A and B is 120 degrees and between phases A and C is 240 degrees. The zero crossings of the 50 Hz phase B voltage are given by:

$$\omega_n t = \frac{2\pi}{3} + 2\pi n \quad (4)$$

where n is a non negative integer. So the expressions of the sub-harmonic three phase system are [1],[19]:

$$u_a = u_m \sin(\omega_o t)$$
$$u_b = u_m \sin\left(\omega_o t - \frac{2\pi}{3}\right) \quad (5)$$
$$u_c = u_m \sin\left(\omega_o t - \frac{4\pi}{3}\right)$$

Assuming that α_B must be one of the zero crossings for the new generated frequencies satisfying (4) for $\omega_o t = \alpha_B$, and combining equations (2) and (3), it yields [1]:

$$\alpha_B = \frac{\frac{2\pi}{3} + 2\pi n}{r} \quad (6)$$

Where r is such that, for positive sequence:

$$r = 1 + \frac{3}{2} n \quad (7)$$

and for negative sequence:

$$r = -1 + \frac{3}{2} n \quad (8)$$

In reference to phase A, and using equations (2)-(4) and (7)-(8), the generated systems becomes [1], [6]:

$$\omega_o t - \alpha_a = 0 \quad (9)$$
$$\alpha_b = \frac{2n\pi + \frac{2\pi}{3}}{r} \quad (10)$$
$$\alpha_c = \frac{2n\pi - \frac{2\pi}{3}}{r} \quad (11)$$

Thus, we deduce the following new system:

$$u_A = u_m \sin(\omega_o t)$$
$$u_B = u_m \sin(\omega_o t - \alpha_b) \quad (12)$$
$$u_C = u_m \sin(\omega_o t - \alpha_c)$$

Some other discrete frequencies generated from the line frequency are 3.33 Hz, 5 Hz and 10 Hz. For each, there are several possibilities of waveforms generated voltages. Fig.4(a-d) illustrate some examples of the generated frequencies: f=7.14 Hz, 12.5 Hz, 16.66 Hz and 25 Hz. We note that the waveforms under the generated new frequencies are not sinusoidal. We note also that the number of zero crossings at 50 Hz is $n_z = 2r$ [6]. Thus there are n_z^2 different possibilities of sub-harmonic voltage waveforms as summarized in

Table 1. In order to obtain the positive torque, the phase sequences of the generated voltage under sub-frequencies have to be positive. Among several possible combinations, the closest to a balanced system is chosen. It is the one corresponding to the highest positive sequence [1]. Thus, for each possibility of generated frequency, the sequences are evaluated using the Fortescue transformation. For the new frequency 7.14 Hz, the results of (+), (-) and zero sequences are presented in Fig.5, where the positive sequence component dominate the other two. Consequently, a positive electromagnetic torque is produced.

Table 1
Sub-generated frequencies

Freq(Hz)	25	16.66	12.5	7.14
r	2	3	4	7
nz	4	6	8	14
n2z	16	36	64	196

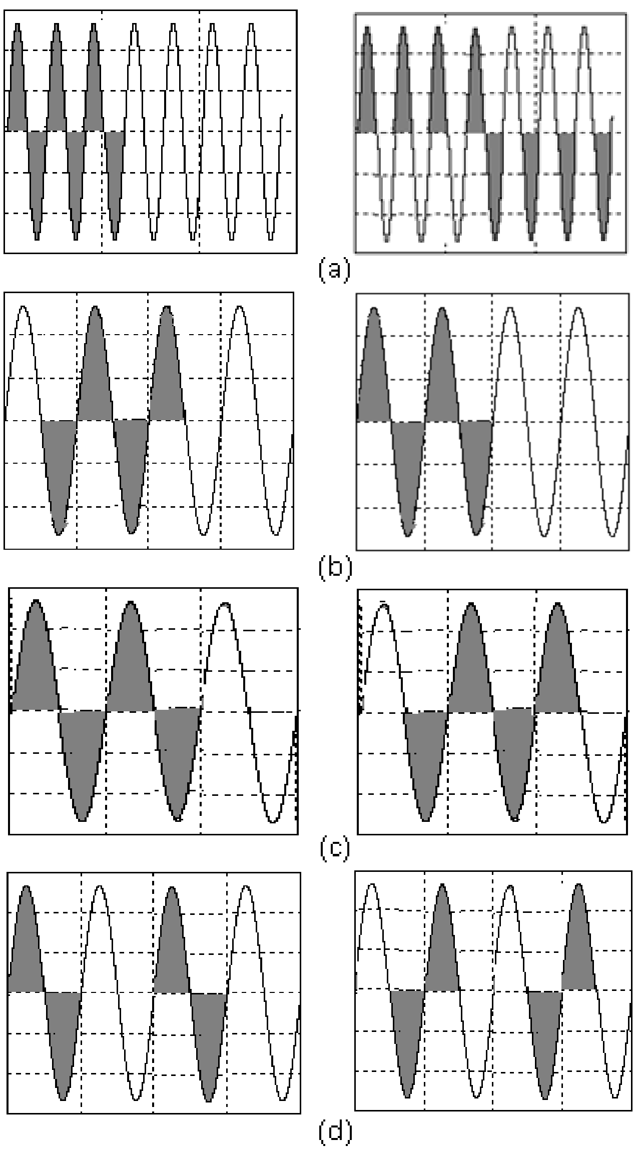


Fig. 4. Examples of generated frequencies: (a) $f_o = 7.14$ Hz, (b) $f_o = 12.5$ Hz, (c) $f_o = 16.66$ Hz and (d) $f_o = 25$ Hz

Fig. 5. The Fortescue sequences for the best generated frequency: $f_o = 7.14$ Hz

3. Simulation results

The simulations were carried out using the software PSIM. The induction motor is delta connected. The motor parameters and name plate data are given in the appendix.

3.1. DOL or Booster starting of induction motor

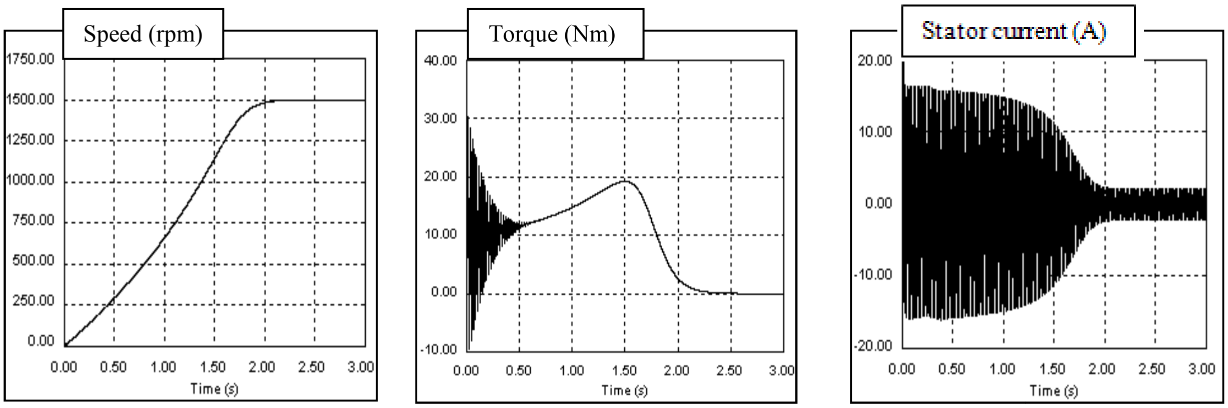
The speed, electromagnetic torque and stator current of the induction motor are depicted in Fig 6. Fig.6.a shows that the induction motor reaches 214 rpm rotational speed in 0.5 seconds and 375 rpm in 0.9 seconds. The rated speed reached in 2 seconds (Fig 6.a). The simulation results in Fig 6.b and Fig 6.c show that the starting electromagnetic torque $T_s = 1$ pu and the stator current $I_s = 6.25$ pu.

3.2. Discrete frequency control starting (DFC)

Using DFC strategy under the generated frequencies 7.14 Hz and 12.5 Hz, plots of the rotor speed, torque, starting current are respectively given in Fig 7-8. As shown in Fig 7, under the 7.14 Hz generated frequency, the rated speed of 214 rpm is reached in 0.1 s, the starting electromagnetic torque reaches 2.5 of the rated torque and the peak value of the starting current reaches 20 A.

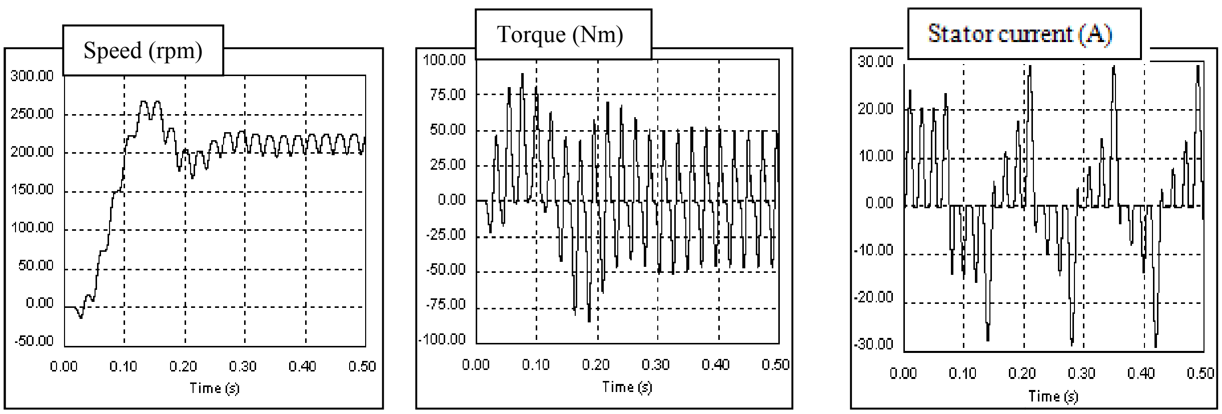
Similarly as shown in Fig 8, under the 12.5 Hz generated frequency the rated speed of 375 rpm is reached in 0.4 s, the starting electromagnetic torque reaches twice the rated torque and the peak starting current value reaches 19 A. Comparison of simulation results between the Booster and the DFC techniques are summarized in Table 2. According to the relation between the starting time and the starting torque: the shorter the starting time is, the larger is the starting torque.

So under this frequency, the average accelerating torque could be estimated by: $C_{acc}=\frac{\Delta\Omega}{\Delta t}$; from which we deduce that C_{acc} generated with the DFC under the



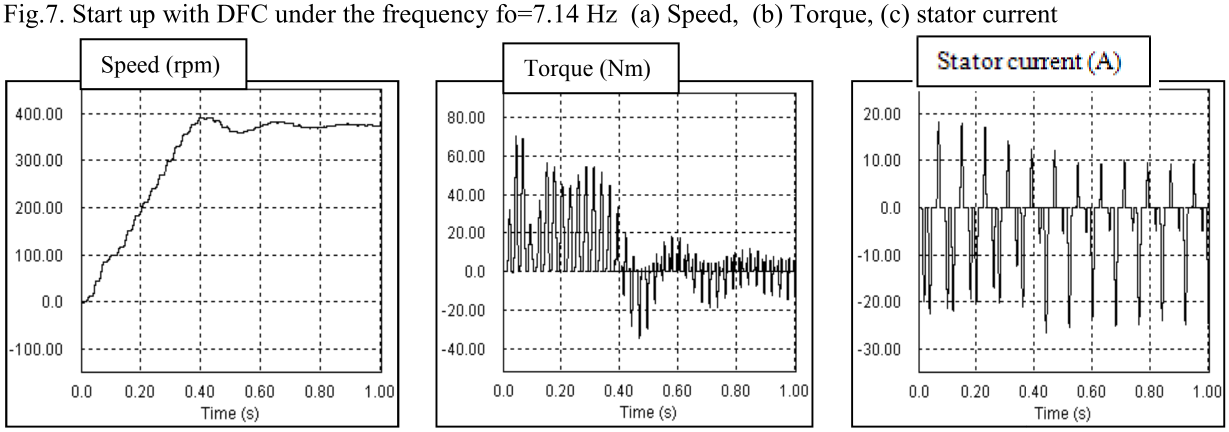
(a) (b) (c)

Fig.6. Direct on line start up of induction motor; (a) speed, (b) torque, (c) stator current



(a) (b) (c)

Fig.7. Start up with DFC under the frequency fo=7.14 Hz (a) Speed, (b) Torque, (c) stator current



(a) (b) (c)

Fig.8. Start up with DFC under the frequency fo=12.5 Hz, (a) Speed, (b) Torque, (c) Stator current

frequencies of 7.14 Hz and 12.5 Hz are respectively about five times and twice the Booster accelerating torque. Thus, as indicated in Table 2, the starting currents with the DFC under these frequencies are respectively 56% and 66% of the starting current with the Booster technique. So, the DFC strategy under the generated frequencies 7.14 Hz and 12.5 Hz improves the induction motor start up characteristics, the starting current and the electromagnetic torque.

Table 2
Simulations results of Booster and DFC starting

		Starting (s) time	Average torque (pu)	RMS current (pu)
Booster	214 rpm	0.5	1	5.2
	375 rpm	0.9	1	5.2
DFC(7.14 Hz, 214 rpm)		0.1	2.5	3
DFC(12.5 Hz, 375 rpm)		0.4	2	3.5

4. Experimental results

The experimental set up is shown in Fig 9. It consists of a squirrel cage induction motor, a three phase balanced supply voltage, three phase AC-thyristors, a Hardware circuit containing a micro controller and a firing circuit, a digital scope for recording currents, speed, torque and the value of average torque. The parameters and nameplate data of the induction motor are given in the appendix

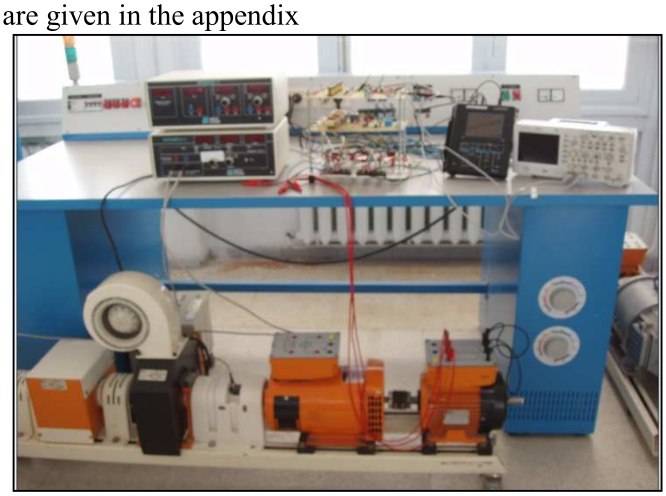
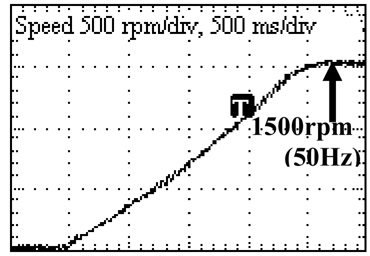


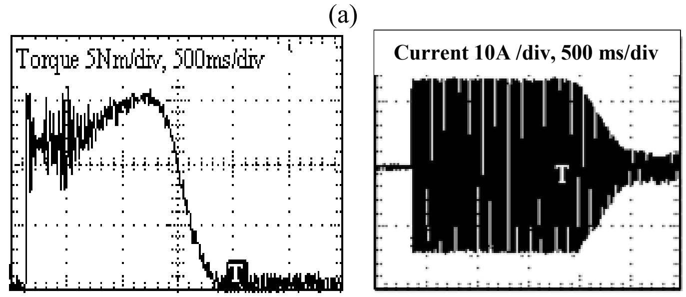
Fig. 9. Photos of the experimental set up

4.1. Booster or DOL starting

Experimental results of the squirrel cage induction motor's direct start up are given Fig 10 (a-c). Fig . 10(a) indicates that the motor reaches its rated speed in 2s. The staring torque and current magnitude are the rated torque and 28 A, as shown in Fig 10.(b) and (c) respectively. The RMS starting current reaches $I_{sB} = 6.25$ pu .



(a)



(b) (c)

Fig. 10. Booster starting under the frequency $f_n = 50\,Hz$, (a) speed starting, (b) electromagnetic torque, (c) starting current

4.2. Start up with DFC (f_o=7.14 Hz and f_o=12.5 Hz)

Starting characteristics with the sub-multiple frequencies 7.14 Hz and 12.5 Hz are illustrated in Fig 11 exhibiting the speed, stator currents and the electromagnetic torque. The experimental starting results of the squirrel cage induction motor under the frequency 7.14 Hz are shown in Fig 11 left. Indeed, the 200 rpm rated speed is reached in 0.14 s. Fig .11.b left shows the wave form of the starting current with a peak value reaching 22 A, and RMS value reaching Is =1 pu. Under this generated frequency, the induction motor starts up with three times the rated torque.

Likewise, with the DFC strategy under the 12.5 Hz generated frequency, the starting speed, stator current and electromagnetic torque are shown in Fig 11 right. It is noted that 375 rpm rated speed is reached in 0.25 s. Fig .11.b right shows that the starting current peak value reaches 22 A, and the RMS value reaches Is =1.5 pu. Fig11.c right shows that with the DFC technique, the induction motor develops an important starting torque reaching 2.5 the rated torque.

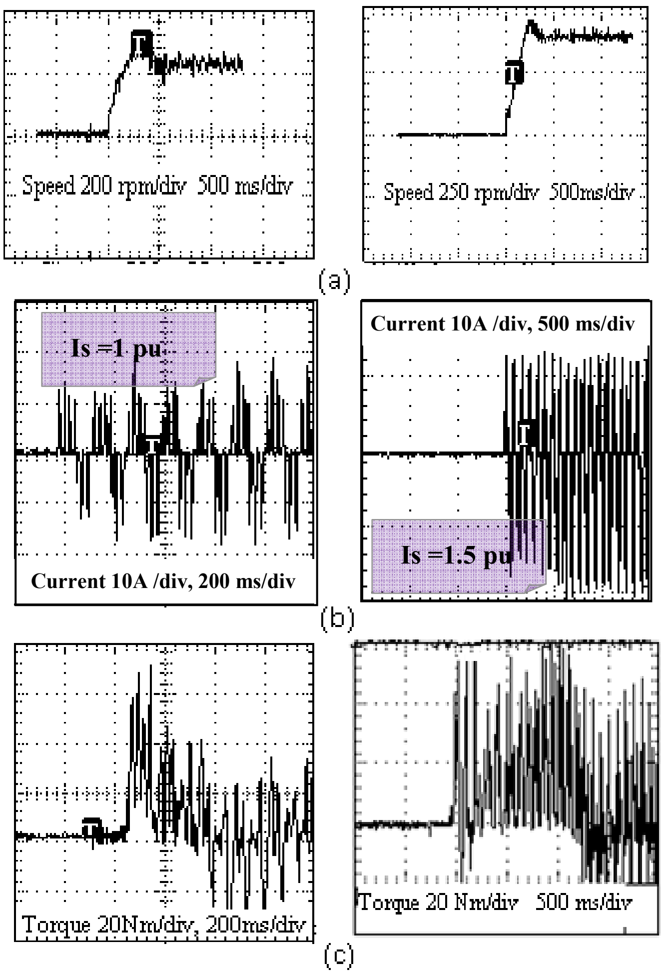


Fig. 11. Start up with DFC: (left): $f_o = 7.14\,Hz\,Hz$ and (right) $f_o = 12.5\,Hz$, (a):speed, (b): stator starting current, (c):torque starting pulsation

4.3. Comparison between Booster start up and DFC start up

✓ **Starting time**: Fig 12 and 13 compare the booster technique and the DFC technique for the frequencies 7.14 Hz and 12.5 Hz, respectively. We note that in order to reach their respective rated speeds of 214 rpm and 375 rpm, the acceleration torque by the DFC technique is more important than by the Booster technique.

These results are summarized in table 3. In order to reach the rated speeds of 214 rpm and 375 rpm under the frequencies of 7.14 Hz and 12.5 Hz, the starting time by the DFC are respectively 35% and 41% of the starting time with the Booster strategy. Thus the starting time needed is significantly reduced by the DFC strategy as compared to the Booster strategy

Table 3
Start up experimental results

		Starting time (s)	Average torque (pu)	RMS current (pu)
Booster	214 rpm	0.4	1	5.5
	375 rpm	0.6	1	5.5
DFC(7.14 Hz, 214 rpm)		0.14	3	2.8
DFC(12.5 Hz, 375 rpm)		0.25	2.5	3

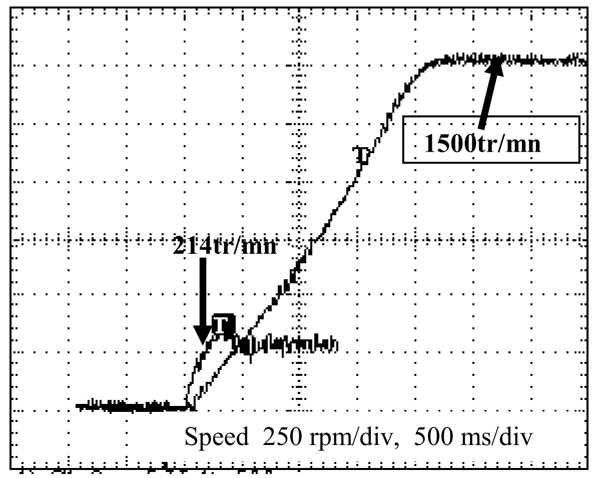


Fig. 12. Speed comparison between Booster technique and DFC strategy under the frequency $f_o = 7.14\,Hz$

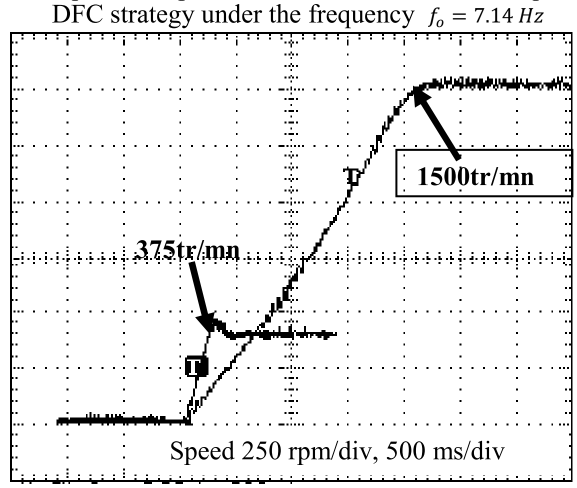


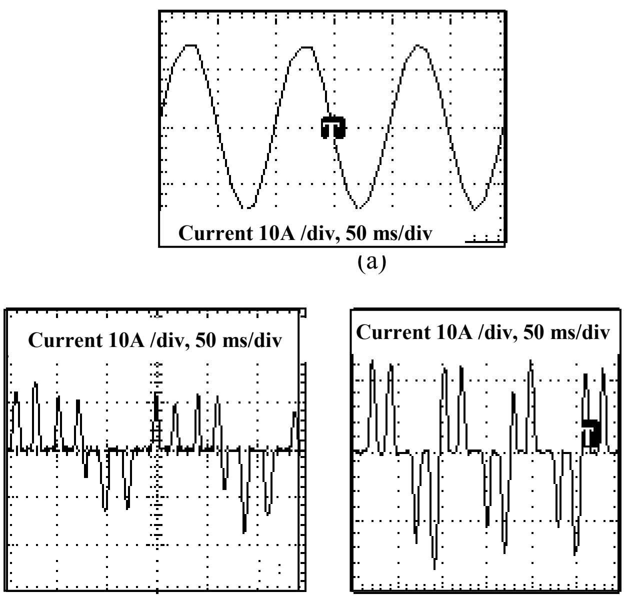
Fig. 13. Speed comparison between Booster strategy and the DFC one under the frequency $f_o = 12.5\,Hz$

✓ **Starting torque**: Referring to table 3, the acceleration torque C_{DFC} under the DFC control and for both generated frequencies 7.14 Hz and 12.5 Hz, is more important than for the $C_{Booster}$ for the Booster technique. The acceleration torque with DFC under 7.14 Hz and the 12.5 Hz frequencies, reaches respectively 300% and 250% of rated torque developed by the

Booster strategy. So, the DFC strategy significantly improves the induction motor performance at starting in terms of electromagnetic starting torque.

Stator starting current: Fig 14 shows the starting current by the Booster strategy and the DFC technique under both generated frequency 7.14 Hz and 12.5 Hz. It is clear that the RMS current with the DFC strategy is significantly reduced compared to the Booster technique. As shown in table 3 the DFC strategy under the generated frequencies 7.14 Hz and 12.5 Hz led to an RMS starting currents equal respectively to 50% and 54% of the Booster starting current. So the DFC allowed a significant reduction of the stator current.

Finally, taking into account the above experimental results, we may confirm that the DFC strategy improves the starting performance of the induction motor when compared to the Booster strategy. These constations agree with the simulation results and show that under the DFC technique, the induction motor reaches the rated speed with an important starting torque under significantly reduced current.



(b) (c)

Fig. 14. Zoom of stator current, (a) with Booster technique, (b) with DFC technique under the frequency 7.14 Hz, (c) with DFC technique under 12.5 Hz

5. Conclusion

This paper presented a new control strategy for induction motor starting based on discrete frequency control (DFC). The proposed technique is based on generating voltage waveforms with sub frequencies of the power supply frequency. The principle of the waveforms generation at sub-multiple frequencies was explained. The generated voltages were analyzed by the symmetrical components method. Among many tested waveforms, the two sub-multiple frequencies: 12.5 Hz and 7.14 Hz, led to the best positive sequence. The proposed control strategy start up performances were simulated and experimentally verified on a laboratory machine. With respect to the classical Booster technique, the DFC technique presented a significant reduction in the starting current down to 24% for the 12.5 Hz frequency, and 16% for the 7.14 Hz frequency. The starting torque has also been significantly improved and the motor could start with the full load. Experimental and simulation results were in good agreement and confirm the wide advantageous applications of the DFC technique as reported in the earlier papers [16-18].

Appendix

Motor data:

Rated voltage: Un=380 V, rated power: Pn=1.5 kW, P=2 pairs of poles , rated speed Nn=1435 rpm, rated current In=3.2 A, the stator resistance is $R_s = 5\ \Omega$, the stator winding leakage inductance is $L_{ls} = 30\ \mathrm{mH}$, the rotor resistance is $R_r = 4.5\ \Omega$, the rotor winding leakage inductance is $L_{lr} = 30\ \mathrm{mH}$, the magnetizing inductance is $L_m = 455\ \mathrm{mH}$, the rated torque is $T_n = 10\ \mathrm{Nm}$.

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