Comparison of instantaneous and average torque control for a Switched Reluctance Motor

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***Abstract*— The purpose of this paper is to compare two different techniques to adjust the reference torque in a speed control loop for variable speed control of switched reluctance machine. The first technique is "instantaneous", i.e., the torque is instantaneously regulated to fit the reference by modulating the current profile with respect to rotor position using the electromagnetic torque characteristics. This data is obtained by finite element calculations.**

The second technique is "averaged" and has to maintain an accurate average shaft torque at a commanded torque level. This goal is achieved by adjusting switching angles and reference current level which is kept constant with respect to the position. Those parameters are tuned off line and tabulated in look-up tables for real time control.

The principles of both methods are discussed in detailed. Simulation results are shown. Conclusions are dressed concerning the advantages and drawbacks of each method.

I. Introduction

Switched Reluctance Motor (SRM) drives are under consideration in various applications requiring high performance applications.This is certainly due to its numerous advantages such as simple and robust construction, low-inertia, high-speed and high-temperature performance, low costs, and fault tolerance control capabilities.

However, several disadvantages like acoustic noise generation and torque ripple are limiting its utilization compared to other kind of machines. Torque pulsations are inherent in SRM due to the doubly salient structure of the machine. The reluctance principle for torque production is utilized in these machines, where the phases operate independently and in succession. In particular, at low speeds, torque ripple can generate speed oscillations and may stimulate resonant frequencies in the mechanical parts of a drive train [1]. Therefore, different techniques have been proposed so far for torque-ripple minimization in switched reluctance drives. Mechanical design can be used to minimize inherent torque ripple [2]. The drawback of these approaches is the reduction of the maximum achievable torque due to an increased effective air gap. When the motor is already built, which corresponds to our case, torque ripple can only be minimized by using electronic control techniques.

The first part of this paper presents a review of various approaches used in instantaneous switched reluctance torque regulation. One of this attractive approaches is adopted in this work and is tested on a prototype. In the second part, the classical averaged torque control will be discussed and tested. Control variables, i.e., turn-on angle ψ, conduction angle θ_p and reference current I_{ref} are stored in lookup tables in order to minimize torque ripple at low speeds and maximize efficiency at high speeds. In both methods, the same speed and current regulators are used. Only the transformation of the total desired torque into individual phase current reference varies. Simulations tests are carried out in order to validate this work. Finally, a comparison of this two techniques is dressed in order to make conclusions about the usefulness of each of them.

II. Machine characteristics

The considered prototype is a four phases 8/6 SRM whose parameters are specified in the table below.

TABLE I
PROTOTYPE CHARACTERISTICS

Geometric parameters	
Number of rotor poles	6
Number of stator poles	8
Stator outer diameter	143 mm
Shaft diameter	23 mm
Stator pole arc	19.8°
Rotor pole arc	20.65°
Airgap length	0.8 mm
Electric parameters	
Number of phases	4
Nominal power	1.2 kW
Nominal speed	3000 rpm
Nominal voltage	24 V
Indication of protection	IP20

In this study, a numerical tool [3] based on finite element analysis (FEA) is used to generate the electromagnetic characteristics (flux linkage and torque).

Fig. 1 shows the obtained torque curves $T(i, \theta)$, relative to one phase, over one electrical period and for phase currents going up to 100A with an increment of 8.33 A. This calculated data was validated experimentally and will be used in the instantaneous torque control of the machine.

III. Instantaneous torque control (ITC)

Current or torque control constitutes the heart of control in drive systems to obtain the desired high bandwidth in torque and speed responses. In instantaneous torque control, the current reference is computed at each sample time, according

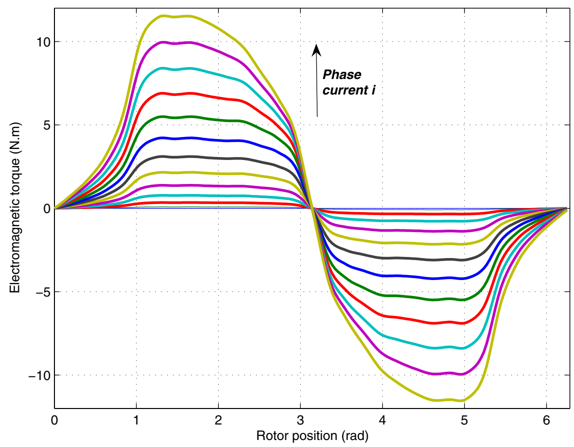

Fig. 1. Electromagnetic torque versus current and rotor position.

to the torque reference and the rotor position. A conventional method for torque ripple minimization is known as current profiling, in which the phase current profile to generate a smooth torque is pre-calculated and stored in the controller [5], [6], [7].

If the individual phase currents can be controlled with a high bandwidth, then the problem of choosing the appropriate current waveforms to ensure low torque ripple becomes the key issue. The production of torque by individual phases must be coordinated so that the total torque tracks the reference value generated by the speed control loops. The torque sharing functions (TSF's) and the associated current or flux waveforms must be designed [5].

Optimal current profiles can be determined by different methods and optimization strategies. In [6], five procedures for minimizing the torque ripple in the SRM were presented. The main idea behind these procedures is to start the optimization from a phase current in the shape of a positive "half-sine" waveform, which corresponds to the positive torque production of the motor, and to control this kind of waveform with a very small number of optimization variables (1-3 variables). As an indication of the torque ripple intensity, the authors chose to use the torque variance of the motor. The simplex method and the genetic algorithm have been adapted to this task. Although it is possible to use the new procedures with lookup table approaches, the main advantages of these procedures are realized in some on line applications but in cases where a torque ripple signal is available. In this case, no prior global tables (table of the current profiles for various velocities, table of the magnetization curves, etc.) are needed.

A comparison between these procedures and the optimum harmonic current injection procedure under the limitation of using the same number of optimization variables shows a clear advantage of the new procedures in both the quality of the solution and the length of the calculation time. This means that under this kind of limitation, these procedures are preferable.

The use of the machine torque, measured or estimated, to implement the torque-ripple reduction techniques on line, decreases the robustness of the algorithm and limits the industrial applications mainly due to cost increase.

Therefore, the authors proposed in [7], an off line current modulation using a neuro-fuzzy compensation scheme. The proposed technique adds a compensating signal Δi_{comp} to the PI speed controller output i_{PI}, which, ideally, should be constant in steady state but producing significant torque ripple. The resulting signal i_{ref} after the addition is used as a compensated current signal for the SRM drive.

The compensating signal is learned off line by a neuro-fuzzy system in order to produce a ripple-free output torque. During the simulation tests, torque ripple was used as the training error variable. Since different SRMs have diverse inductance profiles because of the construction features and varied materials, the scheme proposed in this paper cannot be applied to a motor without a pretraining process to obtain the compensation function.

The torque ripple minimization is of utmost importance during commutation, where overlapping conduction of phases occurs. The concept of torque sharing over an extended overlapping region is treated in [8], [9] and is adopted in this work. The torque control strategy is based on following a contour for each of the phases of the SR motor such that the sum of torques produced by each phase is equal to the desired torque T^*_{tot}. In order to achieve this desired torque, we define a contour function f_{tot} such that :

$$T^*_{tot} = \sum_{k=1}^{q} T^*_k = \sum_{k=1}^{q} T^*_{tot}\, f_k(\theta) = T^*_{tot}\, f_{tot}(\theta)$$

with

$$f_{tot}(\theta) = \sum_{k=1}^{q} f_k(\theta) = 1 \quad (1)$$

Here f_k and T^*_k are respectively the contour function and the requested torque of the kth phase. One possible choice for the phase 1 contour function $f_1(\theta)$ for a four-phase 8/6 SRM is shown on 2. The equation of $f_1(\theta)$ is given by :

$$f_1(\theta) = \begin{cases} 0.5 - 0.5\ cos(k(\theta - \theta_0)) & ;\ \theta_0 < \theta < \theta_1 \\ 1 & ;\ \theta_1 < \theta < \theta_2 \\ 0.5 + 0.5\ cos(k(\theta - \theta_2)) & ;\ \theta_2 < \theta < \theta_3 \\ 0 & \text{otherwhise.} \end{cases} \quad (2)$$

with

$$\begin{aligned} \Delta &= \theta_p - (360/q) \\ \theta_0 &= \psi \\ \theta_1 &= \psi + \Delta \\ \theta_2 &= \psi + (360/q) \\ \theta_3 &= \psi + \theta_p \\ k &= 180/\Delta \end{aligned}$$

where q is the number of phases, ψ is the turn on angle and θ_p is the conduction period.

In motoring mode, the contour function for a phase is nonzero only during its positive inductance slope, i.e.

$$0^\circ < (\theta_0, \theta_3) < 180^\circ \quad (3)$$

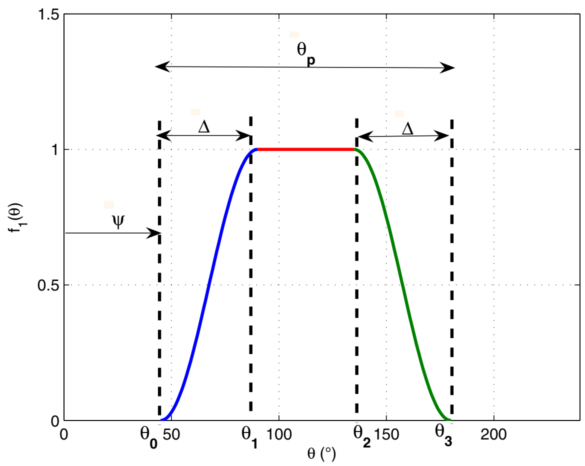

Fig. 2. Contour function of phase 1.

The choice of the reference angles (ψ, θ_p) depends on the inductance profile of a particular motor.
The commutation is designed to take place over a prolonged period for smoothness of operation during transition of current conduction from an outgoing phase to the incoming one. The torque control strategy forces the outgoing phase current to follow a decaying contour rather than allowing it to freewheel naturally. The incoming phase current is also forced to follow an increasing contour by active control.

Once the total reference torque is distributed on the conducting phases, the individual phase reference current is determined using the torque-angle-current characteristics (Fig. 1) that are stored in a tabular form for quick access and retrieval of data. The phase current can be regulated to follow the desired contour by either bang bang control or PWM control. A hysteresis current controller is adopted in this work, which is robust and fast [10]. The current is limited to 100A (maximum current value restricted by the converter).

The overall block diagram of the controller is shown in Fig. 3. An encoder is used to feedback the rotor position continuously to the controller. The torque is regulated in the inner control loop, while the speed is controlled in the outer loop through a PI controller. The desired current is compared with the actual current, and the generated switching pattern is fed to the power converter.

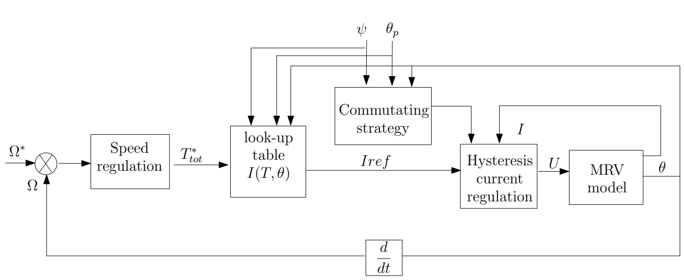

Fig. 3. Block diagram of the SRM drive with ITC.

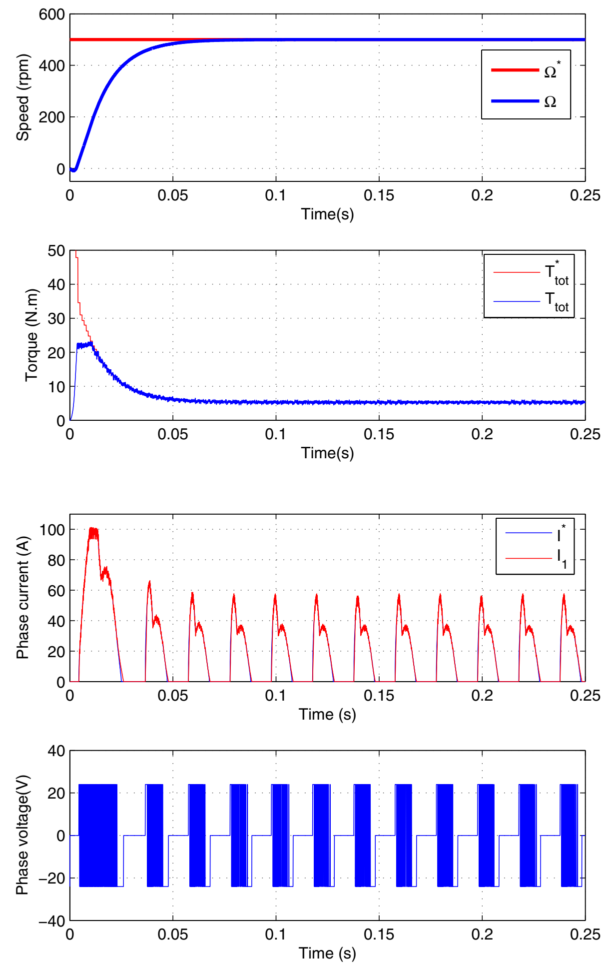

Fig. 4. Simulation results for instantaneous torque control.

Simulations results for a step command from 0 to 500 rpm with a load of 5 Nm are shown on Fig. 4. The figure shows the total reference current and the current produced by the machine. It shows also the wave forms of the reference and actual currents and voltage through the phase 1. ψ and θ_p are chosen to be $0°$ and $180°$ respectively.

An interesting method to regulate the torque instantaneously was introduced in [11]. The important feature of this "Direct Instantaneous Torque Control" (DITC) method is that torque is directly regarded as a control variable and there is no current control loop any more. DITC reacts against the torque error instantaneously with high dynamic response by the torque hysteresis control. Using the reference torque and instantaneous torque values the digital torque hysteresis controller generates the switching signals for the converter based on predefined switching angles. Depending on the deviation of the instantaneous torque from the reference torque, a negative, zero, or positive voltage level is applied to the phase terminals. In a conventional SRM controller, which is based on a current controller either with pulse width-modulation (PWM) or hysteresis control, the torque command has to be translated into a current value first. Next, the switching signals are generated by the current controller to achieve the desired current. In contrast to these conventional controllers, DITC regards torque as a direct control variable and switching signals, i.e., phase voltage, are determined by a comparison between the torque command and the estimated instantaneous torque using a hysteresis torque controller. Moreover, DITC features a feedback control. This makes DITC stable and more accurate against disturbances and parameters uncertainties. DITC appears to be a promising solution for controlling SRMs in high dynamic applications.

IV. Average torque control (ATC)

The ATC is also called "square wave control" [4]. One important feature of this classical controller is that the reference phase current is constant over one excitation period. This leads to small inherent torque fluctuations and high torque ripple during phase commutation. At high speed the torque ripple has a high frequency and is filtered by the moment of inertia of the drive train. In contrast, at low speeds this torque ripple could cause significant speed fluctuations and oscillations in the drive train. This torque ripple is the main drawback of torque control based on constant current regulation.

Three fundamental control variables, i.e., current I_{ref}, turn-on angle ψ, and conduction period θ_p, have to be adjusted. Many combinations of these control variables are possible to operate the SRM drive at one specific torque-speed operating point. However, one suitable combination for one speed-torque operating point should be chosen based on the desired optimization goal, e.g., efficiency or low torque ripple. Using simulations, an optimal set of the control variables over the entire operating range can be obtained. Many classical SRM torque controllers use this approach and rely on lookup tables of the control parameters [4],[12] and [13].

In this work, the lookup tables are generated off line, for the entire torque-speed plane, using a software for SRM simulation [3]. At low-medium speeds, the search is a three-way search for the phase turn-on angle ψ, the conduction period θ_p, and the reference current I_{ref} (see Fig.5). The selected criteria consists in minimizing the torque ripple that is evaluated through the torque ripple factor :

$$k_{ripp} = \frac{T_{max} - T_{min}}{T_{mean}} \tag{4}$$

where T_{max}, T_{min} and T_{mean} are the maximum, minimum and average torque during one conducting period. At high speeds, the electromotive force increases and the DC source voltage becomes insufficient to regulate the current at its reference. The controller enters then in the single pulse mode (see Fig.6). Therefore the search is a two-way search for the phase turn-on and the conduction period angles with the criteria of maximizing the global efficiency (motor+converter).

The bloc diagram for the ATC is shown on the Fig. 7. The structure is the same as in the ITC (same PI speed controller, same hysteresis current controller). The main difference is located in the transformation from torque to current reference.

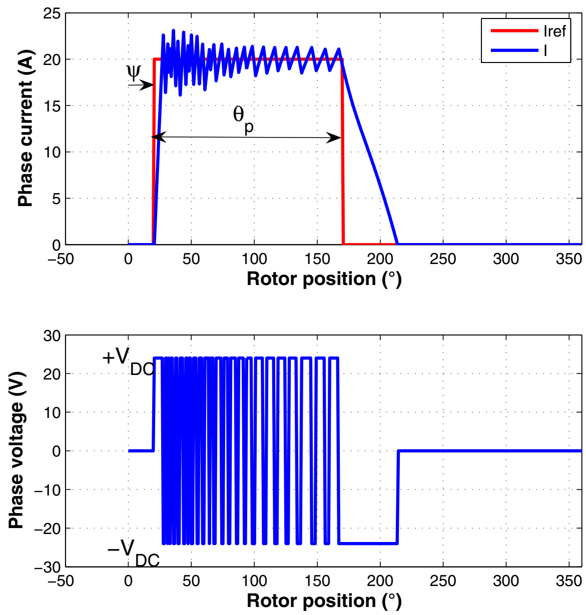

Fig. 5. Hysteresis control.

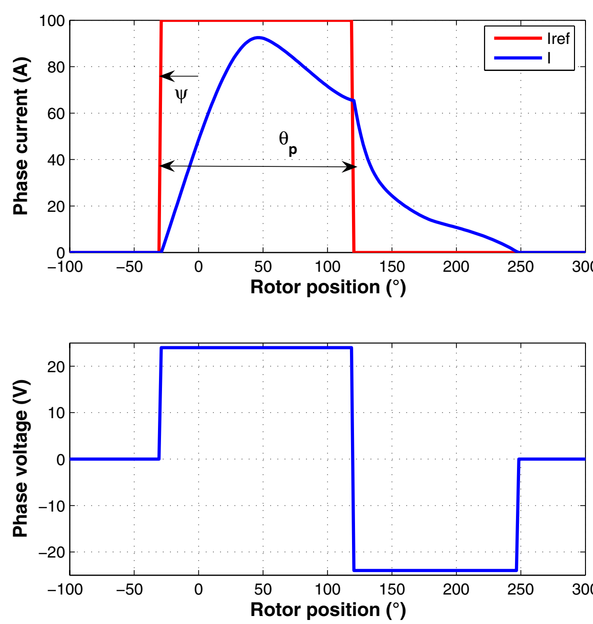

Fig. 6. Single pulse mode.

In this strategy, the total reference torque produced by the speed controller is considered as an average torque over on conducting period. The torque translation into a current reference is located in a look-up table. Linear data interpolation is performed on line to compute the optimal control parameters depending on the operating point. Data interpolation is subject to errors that depends on the table resolution.

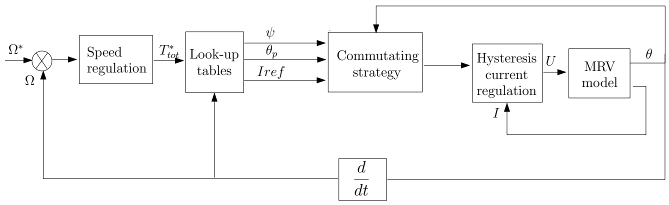

Fig. 7. Block diagram of the SRM drive with ATC.

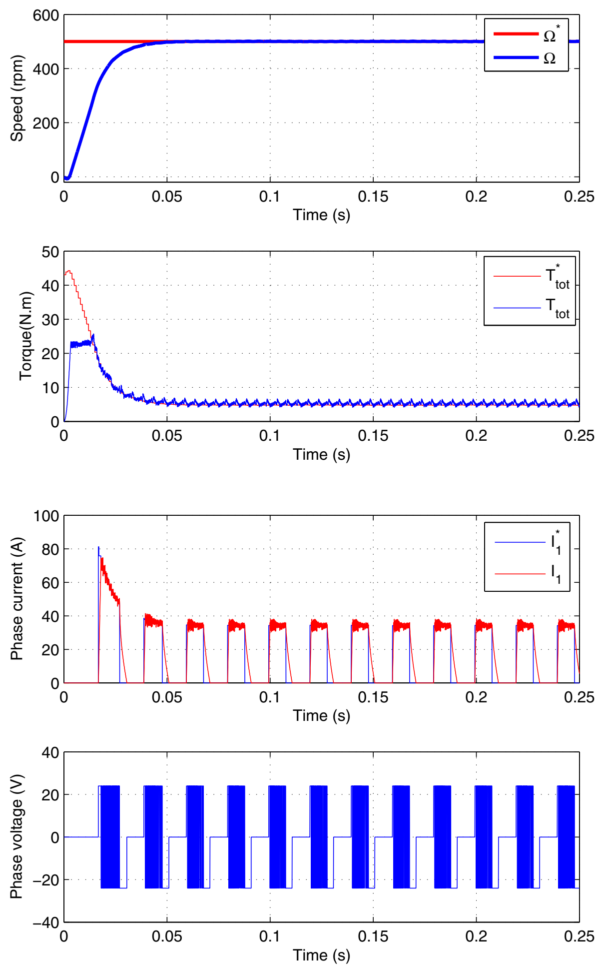

Fig. 8. Simulation results for average torque control.

Simulations results are shown on Fig. 8 for the same operating point (500 rpm, 5 Nm) as in the ITC strategy. Fig. 9 shows the on line variation of the optimal control parameters (ψ_{opt}, $\theta_{p,opt}$, $I_{ref,opt}$) with the operating point in order to minimize the torque ripple.

V. Comparison between ITC/ATC

One important drawback of current profiling is its dependency on an exact sensing of rotor position [4].

Fig. 10 shows a comparison of both methods at steady state (500 rpm, 5 Nm). In ITC the phase current is modulated and varies with the rotor position while it's constant in

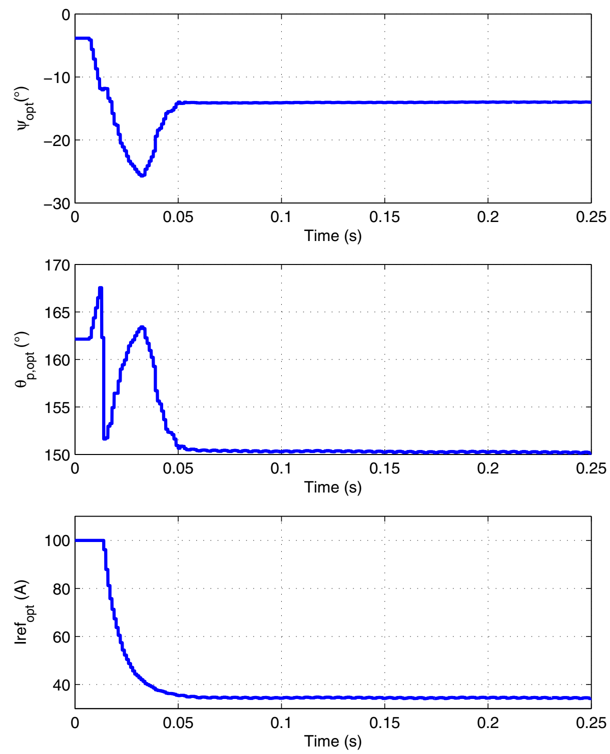

Fig. 9. Variation of control parameters

ATC. Because the torque is instantaneously controlled, ITC is capable of producing lower torque ripple than the optimized ATC for the same operating point as shown on Fig. 10.

So we can say that ITC is ideal for torque ripple reduction, but its performance is limited up to a certain speed. The actual current must be able to follow the contour defined by the function because torque ripple is very sensitive to the current profiles and a slight deviation from the required profile, especially near the commutation region, produces high torque ripple. The back-EMF increases with speed and the current rising rate decreases due to limited inverter voltage [8]. Afterward the motor then enters in the constant power region (single pulse mode) where peak torque production is maintained by controlling ψ and θ_p. At this stage, we are not anymore in an ITC but in an ATC. Average torque produced by the SRM over one electrical cycle can be performed with high accuracy even when the machine operates in single-pulse operation, i.e., when instantaneous back EMF is equal or higher than the dc-link voltage [1].

Another source of limitation for the ITC is the condition imposed by the inequality 3 for positive instantaneous torque production. Advanced angle commutation ($\psi < 0$), necessary for torque maximization at a given speed, is not possible anymore with ITC strategy. Consequently, the capabilities of the motor are not being fully utilized at every rotor speed unless the algorithm commutates to the ATC strategy.

A summary of this comparison is dressed in the table below :

TABLE II

COMPARISON BETWEEN ITC/ATC

	ITC	ATC
Memory space	1 look-up table $T(i, \theta)$	3 look-up tables ψ, θ_p, I_{ref}
Computational effort	maximum 2 cos (2 phases conducting simultaneous.) + 4 interpolations	3 interpolations
Torque ripple	low	significant
Position dependency	significant	low
Covering Torque/Speed plan	partially	completely

VI. CONCLUSION

Two methods for regulating the torque are presented in this paper. The torque is regulated indirectly in the inner control loop through the current regulation, while the speed is controlled in the outer loop through a PI controller.

The ITC method presents the advantage of reducing torque ripple at low speeds and is recommended to be used in applications where torque oscillations cannot be tolerated like in servo drives and robotics. Its performances are restricted to a limited operating range due to the increase of the EMF and the limitation of the DC source voltage.

ATC method is able of covering all the operating points of the torque-speed plane and then maximizing the torque at every speed while maximizing the global efficiency. It's useful in automotive applications for example where maximizing the torque is a primary objective. However it requires some memory space to store the look-up tables of the optimal control parameters.

Finally, we can say that, depending on the type of application, one control method can be suitable more than the other.

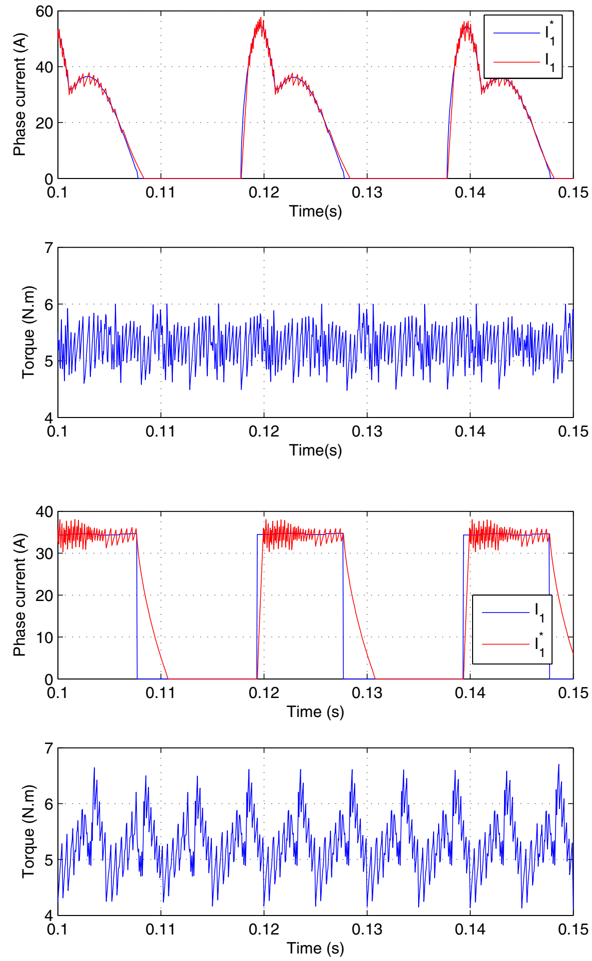

Fig. 10. Comparison of ITC/ATC signals

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