On-line MTPA control strategy for DTC synchronous reluctance motor drives

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Abstract—This paper presents a on-line procedure for the automatic search of the maximum-torque-per-ampere operating region for a synchronous reluctance motor (SynchRM). The algorithm is based on a signal-injection method with a random-based perturbation pattern applied to a common direct-torque-controlled drive. Among motor parameters, only the stator resistance is required to perform the automatic procedure. Simulations and experimental results are presented in the paper, demonstrating the benefits of the proposed algorithm. The solution is easily extended to any AC drive.

Index Terms—AC motor drives, Reluctance motor drives, Losses, Optimisation methods.

I. INTRODUCTION

Recent environmental and energetic issues call for best efficiency solutions for electrical drives. Actually, high-dynamic drives are still required, but besides speed, increased efficiency of the whole drive system could make the difference for a keen customer. Maximum-torque-per-ampere (MTPA) strategies are a smart answer to the call for efficiency. In principle, the target of MTPA strategies is to deliver the electromagnetic torque with the lowest current magnitude. In this way, copper losses are minimised and the overall system efficiency is increased, at least as long as copper losses are dominant.

Modern AC drives usually implement either field oriented control (FOC) or direct torque control (DTC). In the following, a short review of MTPA applied to those technique will be presented.

One of the first examples of automatic MTPA search algorithm is presented in [1], in which a FOC algorithm is integrated with an automatic procedure aimed to minimize the input power. The major drawback is that the d axis current i_d is perturbed with a step-like signal, and the convergence is very low (in the order of minutes).

Another solution, which minimizes the input power, is presented in [2]. The drawback, there, is that steady-state is never reached, since the method foresees a continuous, slow current chattering around the minimum loss operating point. In addition, the algorithm suffers in presence of noisy input power signals.

Other solutions, as [3], [4], and [5] implement MTPA strategies that need the knowledge of machine parameters,

including their non-linearity, as self- and mutual inductances, and possibly the iron losses. It is quite intuitive that the more precise the machine model, the more effective the MTPA implementation. While often computationally not intensive, those approaches definitely requires both a measurement batch on the motor and an off-line data pre-processing.

In [6], again, a conventional FOC algorithm is merged with a MTPA strategy. The problems are incidental to the minimization procedure, which calculates the MTPA point temporarily overriding the speed controller. The approach may fail if the initial working point is far away from MTPA, since a little current angle deviation may cause a relatively high change in torque. Alike the former methods, the torque calculation needs the knowledge of the motor inductances, and no information about the convergence speed has been found in the paper.

Another interesting solution is proposed in [7]. The paper focuses on the MTPA control of an interior permanent-magnet synchronous machine. Both current and voltage limitations are considered to derive proper equations for the current references in a standard FOC drive. The solution is promising since it can work during transients, but there is again the need of a precise knowledge of both the d and the q axis inductances.

The latest solution for an automatic MTPA search in FOC drives is presented in [8]. The MTPA is sought by varying the current vector angle of a common FOC algorithm, looking for the changes in the current magnitude reference signal generated by the speed PI controller. While attractive because of the simplicity of the MTPA detector, a drawback is represented by the injected perturbation signal waveform, which is sinusoidal. This can constitute a problem with sensitive loads, in particular when the sinusoid frequency is close to a mechanical resonance. On the other hand, the great advantage of this solution is that the signal injection skips the need of an accurate drive model. The parameters are still necessary, but for the FOC implementation, and not for the MTPA itself. A more recent combination of [8] and [1], which proves the industry interest in signal injection-based procedure, was presented in [9].

To the Authors' knowledge, and opposite to the aforementioned FOC schemes, the DTC-based AC drives have been scarcely investigated from the MTPA point of view. This is probably due to the fact that the DTC drives extremely fast dynamics fits for to servo applications, in which the focus remains on transient behaviour. But there are other emerging applications, as in mining and steel industry, in which the energy saving issue is going to play a major rule. DTC technology is quite mature, and in most conventional schemes a fast,

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robust and reliable torque production is obtained by stating a proper flux-linkage angle, as proposed by [10]. Nevertheless, as claimed by the Authors themselves, the drive operates at constant flux-linkage magnitude at all loads, resulting in a probable lack of efficiency at light loads.

There are few examples of efficiency-optimization solutions for DTC schemes. One of them is [11], which deals with steady-state efficiency optimization in DTC control of permanent magnet synchronous motors. The best-efficiency stator flux linkage reference is found from an off-line procedure which aims to minimise electrical losses in the motor for a wide operating range. On-line computational effort is limited to the access of a look-up table (LUT) which stores the flux linkage reference as function of the torque and speed value. As for many FOC-based solutions, the method requires the knowledge of inductances and resistances (stator and core loss) of the motor. Further developments of this work were reported in [12], where it is recognized that the best-efficiency stator flux linkage value is not the optimum one for the fastest torque response. The paper presents a solution which combines itself to the best-efficiency LUT, and selects a proper flux linkage reference for fast torque transients only during start-ups.

The proposed work aims to get an energy-optimised drive, by combining the simplicity, speed and robustness of DTC control (in its original form, thus without voltage space vector modulation) with a parameter-insensitive, injection-based MTPA strategy. The signal injection is operated in the flux magnitude reference signal of the DTC drive, either at steady state or during the constant-torque transients, and by observing the changes in the measured stator current magnitude. A random-number-generation pattern is chosen as perturbation signal instead of a pure sinusoidal signal. One positive side-effect of the approach is that the formulation is general enough to allow its extension to permanent magnet motors, and induction motors drives as well.

The paper is organised as follows. In Sect. II, some basics on the SynchRM and the DTC approach will be discussed. Sect. III is devoted to the MTPA strategy and the details of the procedure. Sect. IV presents some simulation results, while Sect. V shows the experimental results. A conclusive discussion ends the paper.

II. DTC FOR SYNCHRONOUS RELUCTANCE MOTORS - BASIC CONCEPTS

The space vector equation that describes the motor dynamics in a reference frame fixed to the stator coordinates $\alpha\beta$ is:

$$u_{\alpha\beta} = R_s i_{\alpha\beta} + \frac{d\lambda_{\alpha\beta}}{dt} \quad (1)$$

where R_s is the stator resistance, $u_{s\alpha\beta}$ is the stator phase voltage space vector, $i_{s\alpha\beta}$ is the stator phase current space vector and $\lambda_{\alpha\beta}$ is the flux linkage space vector. In a dq synchronous reference frame rotating with the rotor electromechanical angle ϑ_{me} , the vector equation (1) becomes [13], [14]:

$$u_{dq} = R_s i_{dq} + \frac{d\lambda_{dq}}{dt} + j\omega_{me}\lambda_{dq} \quad (2)$$

where $\omega_{me} = p\omega_m$ is the electromechanical speed, p is the number of pole pairs and ω_m is the mechanical speed.

Electromechanical torque and load equations complete the system model:

$$\begin{aligned} \tau &= \frac{3}{2}p(\lambda_d i_q - \lambda_q i_d) \\ \tau &= J \frac{d\omega_m}{dt} + B\omega_m + \tau_L \end{aligned} \quad (3)$$

In (3), λ_d and λ_q are respectively the d and q components of the flux linkage space vector, i_d and i_q are respectively the d and q components of the stator phase current space vector, τ_L is the load torque, J is the load inertia, B is the viscous friction.

For DTC purposes, the first of (3) should be expressed in terms of flux linkage magnitude $|\lambda|$ and flux linkage angle δ with respect to the dq reference frame [15]. Fig. 1 reports the nomenclature in case of a motor with one pole pair ($p = 1$). Substituting $i_d = \lambda_d/L_d$ and $i_q = \lambda_q/L_q$, where L_d and L_q are the direct and quadrature inductances (which in general are function of i_d and i_q), and $\lambda_d = |\lambda| \cos(\delta)$ and $\lambda_q = |\lambda| \sin(\delta)$ in the first of (3), leads to:

$$\tau = \frac{3}{4}p \left(\frac{1}{L_q} - \frac{1}{L_d} \right) |\lambda|^2 \sin(2\delta) \quad (4)$$

Fig. 1. SynchRM's synchronous reference frame.

Expression (4) represents the base equation of a DTC algorithm for SynchRMs. The torque is changed either by varying the flux linkage magnitude $|\lambda|$ or the flux linkage angle δ with respect to the reference frame dq . A fast torque change is obtained by a variation of δ [15], while a $|\lambda|$ variation is normally used to change the motor operating region (flux weakening, for example) or to reach particular working conditions (MTPA, for example). Fig. 2 reports the general block schematic of a DTC algorithm for SynchRMs, including speed control and completed with a MTPA detector block for flux linkage reference generation.

The speed reference is compared to the actual speed and a proper torque reference is generated by a simple PI control. Usually, the torque reference also feeds the MTPA detector block, which is responsible of the flux linkage reference generation. In the present work, the input $|\tilde{\lambda}|^*$ was kept separate, and manually set to test the effectiveness of the MTPA search. Torque and flux linkages references are compared with the their estimated values, and then processed by the τ -and- $|\lambda|$ comparators, which are usually composed by two- or three-level hysteresis blocks. Then, the request of torque/flux linkage variations are sent to the switching logic LUT block, which generates the appropriate commands S_a , S_b and S_c to the voltage inverter switches.

Fig. 2. DTC algorithm block scheme.

Actual (or estimated, as in the present work) phase voltages and measured phase currents, together with stator resistance, are requested for the estimation of the flux linkage and torque, according to (1) and the first of (3) respectively. The estimator also gives the flux linkage sector, which is necessary for the correct use of the switching logic LUT.

III. THE PROPOSED MTPA PROCEDURE

A. Concept of the injection-based algorithm

Fig. 3 shows the contour plot, drawn for one of the SynchRMs used in the simulation stage of this work, of the torque τ and the flux magnitude $|\lambda|$ as function of the phase current magnitude $|i|$ and the current angle ϑ_i , which is the angle of the current space vector with respect to the d axis.

Fig. 3. τ and $|\lambda|$ contour plot as function of $|i|$ and ϑ_i .

The minimum current magnitude for a given torque τ , which is referred as $|i|_{MTPA}$, is obtained with a unique flux linkage magnitude value, namely $|\lambda|_{OPT}$. In other words, if the motor is not working in the MTPA point, the flux magnitude value is different from $|\lambda|_{OPT}$. For any given $(\tau, |\lambda|)$ couple, there is a relationship between a small $|\lambda|$ variation and the subsequent $|i|$ variation. In particular, three different cases can occur. If $|\lambda|$ is above the $|\lambda|_{OPT}$ value (point 1 in Fig. 3), then a flux magnitude decrease will correspond to a current magnitude decrease, while a flux magnitude increase will correspond to a current magnitude increase. Conversely, if $|\lambda|$ is below the $|\lambda|_{OPT}$ value (point 2 in Fig. 3), a flux magnitude decrease will correspond to a current magnitude increase, and a flux magnitude increase will correspond to a current magnitude decrease. If $|\lambda|$ matches the $|\lambda|_{OPT}$ value (point 3 in Fig. 3), then either a flux magnitude increase or decrease will cause a current magnitude increase anyway.

Such cases are depicted in Fig. 4, where the $|i|$ variation is plotted as function of the $|\lambda|$ variation. Plots have been obtained with a simulation of the DTC-controlled SynchRM, forcing the flux linkage reference to vary in a random manner around respectively three different operating points: above, below and equal to $|\lambda|_{OPT}$ respectively.

B. The MTPA detector

It is clear from Sect. III-A that the MTPA point is retrievable from a comparison between an injected perturbation on the flux linkage magnitude $|\lambda|$ (or, equivalently, on its reference $|\lambda|^*$) and the resulting current magnitude $|i|$. As a first step, the concept can be proved by adding a pure sinusoidal perturbation to the flux linkage reference signal $|\lambda|^*$ of the DTC scheme (see Fig. 2), generating a pattern similar to Fig. 4, but in the time domain. The result is reported in Fig. 5a, where the simulation has been carried out at the nominal speed and load for the SynchRM. The flux linkage reference has been forced to vary from 0.85 to 1.15 times the $|\lambda|_{OPT}$ value. At the same time, the current magnitude $|i|$ has been acquired, low-pass filtered to remove the DTC-related ripple, and high-pass filtered to remove the mean value.

There is an evident out-of-phase relationship between the $|\lambda|$ and $|i|$ perturbations below the MTPA point, while the curves are in phase when the operating point is above the MTPA region. The product of the two perturbations is shown in Fig. 5b. A low-pass filtering action, aimed to remove the oscillatory profile, returns a non-zero signal when the motor is not working around the MTPA point. This key feature is used to retrieve the MTPA point on-line. The complete MTPA detector has been implemented as shown in Fig. 6.

As a first important remark, a FFT analysis of the torque produced by the drive has revealed the presence of a non-negligible residual torque harmonic at the frequency of the perturbation, even if it falls within the DTC tracking capability. Therefore, instead of using a pure sinusoidal perturbation for the flux reference signal, a pseudo-random signal with uniform distribution (RNG block, Fig. 2) has been superimposed to the flux linkage reference input $|\tilde{\lambda}|^*$. This solution spreads the harmonic content of the injected signal on a wider frequency range, smoothing torque harmonic peaks typical of the pure sinusoidal signal injection, as it will be shown in Sect. V.

As mentioned, the DTC ripple and the mean value on $|i|$ are removed by the first-order low-pass filter LPF_1 with time constant T_{lpf} and the first-order high-pass filter HPF with time constant T_{hpf} respectively. As shown in Fig. 6, the same filters are applied to the perturbation signal, to maintain the

Fig. 4. $|i|$ vs. $|\lambda|$: variation with (a) $|\lambda| = 1.1 |\lambda|_{OPT}$, (b) $|\lambda| = 0.9 |\lambda|_{OPT}$ and (c) $|\lambda| = |\lambda|_{OPT}$.

Fig. 5. (a) $|\lambda|$ and $|i|$ perturbations in different operating points, (b) $|\lambda|$ and $|i|$ variations product.

Fig. 6. Schematic of the MTPA detector.

same phase relationship between the two signals. According to the procedure outlined in the last part of Sect. III-A, the demodulation is obtained by the cascade of the product and the low-pass filter LPF_2 , with time constant T_{detect} . The last block of the MTPA detector is a PI controller (R_{PI} block) with proportional gain K_{pc} and integral time constant T_{ic} , which generates a compensation signal $|\lambda|_{comp}^*$ that is subtracted from the flux magnitude reference.

The relationship between perturbations of Fig. 5a somewhat recalls what has been verified in [8]. However, the concept is here slightly different. In [8] a sinusoidal signal is used to perturb the phase angle of the current vector in a common FOC algorithm, looking for the changes in the current magnitude reference signal generated by the speed PI controller. The

method links the MTPA perturbation frequency to the speed controller bandwidth, since the latter has to compensate the disturbance, while maintaining a constant output torque. In this work, the speed PI controller generates a torque reference and the DTC inner block is responsible of maintaining a constant output torque. As a consequence, the perturbation frequency has an upper bound given by the DTC bandwidth, which is several times greater than that of the speed loop. But other factors intervene in the choice of the most suitable MTPA dynamics. The MTPA detector relies on the changes of the measured current magnitude induced by changes in the flux linkage reference, and thus in the actual flux linkage. Consequently, the algorithm works properly when current magnitude changes are not related to a torque change, that is the motor is operating at steady-state or during a constant-torque transient. In principle, in order to avoid interference between MTPA and DTC, the MTPA dynamics should be taken 5 to 10 times lower than that of the DTC. This would lead to a MTPA dynamics close to that of the speed loop. An even slower MTPA dynamics could fit for some applications, characterised by extended steady state operations. On the opposite, MTPA dynamics might be increased for applications with short constant-torque periods, with an upper bound set by DTC bandwidth, as said before. Therefore, the frequency range of the MTPA dynamics is actually large, but the best value is application-driven. In the following, for the sake of generality, the MTPA control block discrete-time base will be denoted as T_p , separated from the DTC sampling period T_c .

As a last remark, it is confirmed that the proposed MTPA strategy does not rely on a magnetic model of the SynchRM. The MTPA exploits the flux linkage amplitude estimation of the DTC scheme, which is obtained from (1), by integration. It is evident that if the DTC flux estimator model includes the iron losses, the MTPA algorithm would inherently consider iron losses too. In other words, the proposed MTPA trusts on the already available flux estimate only.

C. The selected pseudo-random number generator

A custom pseudo-random generator with uniform distribution has been chosen, looking in the literature for a very simple but still effective solution, easily implementable in a drive.

It has been found that a very interesting class of pseudo-random generators with uniform distribution is the one called “The Mother of All”, which is a result of the work of G. Marsaglia [16]. This class is suitable for an implementation in electric drives since the random numbers are generated as a result of simple sums, multiplications and some binary operations. As an example, the integer 16-bit generator shown in Fig. 7 is obtained with the following algorithm:

$$\begin{aligned} S_k &= 30903x_{k-1} + (S_{k-1} \gg 16) \\ x_k &= S_k \& 65535 \end{aligned} \quad (5)$$

where x_k represents the actual pseudo-random generated number. Note that the generated x_k are in the range of $[0, 2^{16} - 1]$, so that 2^{15} has been subtracted from the output to obtain a balanced random signal around zero. It is also worth to note that the initialization values for the first seeds x_0 and S_0 are random (just two different values stored in two registers, no need for random seed generation every time the drive is turned on).

Fig. 7. 16-bit pseudo-random number generator.

The algorithm will produce a sequence with a period greater than 2^{29} with a uniform statistical distribution, provided that the initial seeds S_0 and x_0 are different from zero [16]. Considering, as an example, a new number generation every $25 \mu s$ (which is the smallest DTC period in the simulations), the sequence will have a period greater than 13422 seconds (approximately 3.7 hours). This generator is therefore suitable for the MTPA search algorithm, because it combines both simplicity and a very long period generation (the longer is the periodicity of the generator, the broader and flatter is the harmonic content, as demonstrated in [17]).

IV. SIMULATION RESULTS

Many simulations have been carried out to prove the effectiveness of the MTPA detector, using the motor parameters reported in Table I.

Table I
SYNCHRM PARAMETERS.

Rated power	13.70 kW
Rated current	31.4 A
Rated torque	87.2 Nm
Rated speed	1500 rpm
Rated frequency	50 Hz
Rated voltage	378 V
Rated stator flux linkage	0.83 Vs
Pole pairs	2
R_s	0.198 Ω

Before testing the MTPA algorithm, three different flux linkage estimators for the DTC scheme were merged with the DTC algorithm and compared by simulation. Their parameters were tuned to obtain the best tracking capability. An example of flux estimation transient from no load to full load at nominal speed is shown in Fig. 8.

Fig. 8. Flux linkage estimation comparison during a no load to full load transient at nominal speed (simulation).

The first solution (FE_a) is described in [18], and expresses (1) in a reference frame synchronous with the flux linkage space vector. It can be demonstrated that the flux linkage magnitude is obtained from the real part of the space vector equation by integration of the back-electromotive force (bemf), while its angle is obtained from the imaginary part of the equation (and the knowledge of the flux linkage magnitude) because of the presence of a cross-coupling term. The estimated angle is fed back to transform the bemf ($u_{\alpha\beta} - R_s i_{\alpha\beta}$) in the rotating reference frame.

The second approach (FE_b) is described in [19]. The overall idea is that flux linkage and bemf vectors should be 90 degrees apart while rotating in the fixed stator reference frame $\alpha\beta$. In other words, the scalar product between flux linkage and bemf should be zero in all time instants. Should an error in the flux estimation occurs, a non-zero scalar product between flux linkage and bemf appears. This information can be exploited to correct the flux linkage estimation with a feedback scheme which comprises a PI regulator.

The third approach (FE_c) is described in [20]. In that work and the related references, it was observed that the derivative of the scalar product between the flux linkage estimate and the measured stator current, together with the phase of the estimated flux linkage, indicates the direction of the needed

correction for the flux linkage estimate. Thus, the derivative of the scalar product is multiplied by the λ_α and λ_β components, multiplied by a gain and then fed back to the bemb before the actual integration in the $\alpha\beta$ frame.

The third solution (FE_c) gives an estimate almost superposed to the actual flux linkage (Fig. 8), and therefore it was selected for the present work. The structure of the flux estimator was further analysed by simulations, by feeding the estimator with different sinusoidal inputs with increasing frequency. Due to the non-linear structure of the scheme, it was found that the phase delay between actual flux linkage and estimated flux linkage was practically not varying in the frequency range of interest (from zero to the nominal frequency of the motor reported in Table I). On the other side, the estimated flux linkage magnitude was slightly different with respect to the actual one, the difference being related to the value of the feedback gain. It was found that an increase of the feedback gain led to a faster settling time removing the drift problem, but it also produced greater amplitude errors especially at frequency below 10 Hz. In any case, error values were dependant on motor parameters, and a proper gain selection led to almost negligible errors.

The MTPA detector was simulated and tuned. Table II shows the chosen parameters.

Table II
MTPA DETECTOR PARAMETERS FOR THE SIMULATIONS.

T_p	250 μs
$T_{perturb}$	$1/(2\pi \cdot 20)$ s
T_{lpf}	$1/(2\pi \cdot 500)$ s
T_{hpf}	$1/(2\pi \cdot 10)$ s
T_{detect}	$1/(2\pi \cdot 10)$ s
K_c	1 Nm/(rad/s)
T_{ic}	0.007 s

Fig. 9 shows respectively the flux linkage magnitude, current magnitude and speed during typical operation. For the motor used in both the simulation and experimental results, a finite-elements analysis (FEA) was available. That data were exploited to get the best flux linkage reference $|\lambda|_{OPT}$. Three main time steps occur in the simulation, each of them marked in the figures with vertical dashed lines. At 1.5 s the flux linkage magnitude is decreased to 90% of the optimal value. At 1.8 s the perturbation is started, at 2 s the PI controller is activated and at 3.3 s the procedure is manually deactivated.

As it can be seen, the overall system moves towards the minimum current region after the flux linkage perturbation. At the beginning, while the procedure is finding the right minimisation direction, current magnitude increases. Speed is almost unaffected by the process. The simulations confirm that the proposed strategy, after the perturbation, brings back the operating point almost exactly to the initial (correct) one.

Convergence speed, as well as the time base of the MTPA detector, have been studied by simulations. A lower sample time for the MTPA detector leads to a more damped system response. In any case, the response of Fig. 9b, which has been obtained with a sample time $T_p = 250 \mu s$, can be considered acceptable. As expected, parameter T_{lpf} has light influence on

system dynamics. On the contrary, appropriate values of T_{hlf} and T_{detect} should be selected, in order to avoid interference between the filters. In other words, the high-pass filter impulse response should be faster than that of the detector filter, so that the latter is able to find the mean value of the waveform of Fig. 5b. As regards the PI controller parameters K_{pc} and K_{ic} , they can be profitably related to those of the speed controller. In this case, the proportional gain has been set to one tenth of the speed controller one, while maintaining the same integral time constant. Some tests revealed that the MTPA detector works well even with the same PI parameters as those of the speed controller, but with a noisier response.

V. EXPERIMENTAL RESULTS

The proposed MTPA procedure has been tested on the same SynchRM simulated in the previous section. The experimental setup was composed by a SynchRM as controlled motor, an induction motor as load motor, a torque-meter on the common shaft and a power analyser for current/voltage measurements before and after the SynchRM inverter.

Different experimental measurements were obtained while the motor was running in different conditions (no/half/rated load, half/rated speed). Fig. 10 and Fig. 12a show the results obtained for an operating point of 50% of nominal speed and 50% of nominal load, while Fig. 11 and Fig. 12b show the results obtained for the rated load and speed condition.

The flux linkage reference signal $|\lambda|^*$, before the activation of the MTPA procedure, was fixed in both cases to different values which were recognized a-priori as wrong MTPA values. The MTPA procedure was running on a time base of $T_p = 10$ ms.

In both cases, the MTPA search procedure has led to a lower current magnitude with respect to the initial operating point. In the first case, the actual current magnitude is reduced by 10% with an increase of slightly more than 15% of the flux linkage. In the second case of full speed/full load condition, the current magnitude reduction is approximately 5% with a 10% increase of the flux linkage. It is worth to note that a starting value of the flux linkage close to the rated one is preferable, since too small values could prevent the motor to deliver the due torque under loaded conditions at drive start-up.

A relevant issue is that speed and torque are not significantly affected by the injected perturbation while the MTPA procedure is activated. Information about the change of current amplitude can be fully ascribed to the flux linkage magnitude change.

The MTPA procedure was then deeply investigated, with several different values of initial flux linkage values and load/speed conditions. By maintaining the same operating point, it was found that the final $|i|_{MTPA}$ was always the same regardless the initial value of $|\lambda|^*$. Once the $|i|_{MTPA}$ value was reached, a manual adjustment to the flux linkage reference (and so, to actual one) did not show any improvement, that is any other flux linkage statement resulted in a current higher than $|i|_{MTPA}$.

FFT measurements were also performed on the torque signal, using a torque-meter mounted on the shaft, and reported

Fig. 9. Profile during MTPA automatic search: (a) $|\lambda|$, (b) $|i|$, (c) ω_m .

Fig. 10. Experimental tests (50% of rated speed, 50% of rated load): (a) mechanical speed, (b) torque, (c) $|\lambda|^*$, (d) $|\lambda|$, (e) injected perturbation, (f) PI compensator output.

in Fig. 13. The figure reports the torque harmonics for a 2-Hz sinusoidal injection, compared to those of the random pattern injection and the case of no injection. The motor was working at full load at a mechanical speed of 200 rpm. The torque mean value was removed, and only the low-frequency torque harmonics were reported, since the higher ones were almost the same for both injections. Nevertheless, along with some mechanics-related harmonics, it is clear that with sinusoidal perturbation the 2-Hz sinusoidal tone is well visible in the torque spectra, while it disappears when RNG pattern is used.

VI. CONCLUSIONS

An on-line procedure for the automatic search of the MTPA operating point for synchronous reluctance motors has been

presented and discussed. The algorithm is perturbation-based and it injects a random pattern into the flux linkage signal reference of a common DTC drive, retrieving information of the MTPA point from the sampled current magnitude.

The proposed algorithm has been simulated and experimentally verified, proving its feasibility. The simplicity and the effectiveness of the method makes it also suitable for its application to different types of AC drives, as for example internal permanent-magnet motors and induction motors as well.

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Fig. 11. Experimental tests (100% of rated speed, 100% of rated load): (a) mechanical speed, (b) torque, (c) $|\lambda|^*$, (d) $|\lambda|$, (e) injected perturbation, (f) PI compensator output.

Fig. 12. Experimental tests for $|i|$: (a) 50% of rated speed, 50% of rated load, (b) 100% of rated speed, 100% of rated load.

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Fig. 13. Torque harmonics at 100% load (lower frequencies only).

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