Direct Flux Vector Control Of Induction Motor Drives With Maximum Efficiency Per Torque

S. Rajesh Babu[1], S. Sridhar[2]

[1]PG Scholar, Dept. Of Electrical & Electronics Engineering, JNTUACEA, Anantapuramu, A.P., India
[2]Asst.Professor, Dept. Of Electrical & Electronics Engineering, JNTUACEA, Anantapuramu, A.P., India

---

***Abstract*-** This paper proposes a loss-minimizing strategy is proposed for induction motor drives to ensure maximum efficiency operation for a given torque demand. The continuous needs of energy savings require higher efficient electrical drives which uses Adjustable Speed Drives (ASDs). Due to its ruggedness, simple technology, maintenance-freeness and low cost, the Induction Machine (IM) still represents the major energy consumer in ASDs. For applications that require flux-weakening, IMs provide a better solution for ASDs. The efficiency of IM drives can be improved by flux adaptation according to the load demand. The flux adaptation can be done through three categories of loss-minimizing strategies, implemented for scalar or vector control of induction motor drives. These loss minimizing strategies are 1) control of a single motor variable, such as the displacement power factor or the slip frequency 2) the search control, where the motor flux is iteratively adapted to minimize the input power and 3) loss model of the motor and/or the power converter. The proposed strategy directly regulates the machine stator flux according to the desired torque, using an optimal stator flux reference. Therefore, the proposed strategy is suitable for motor control schemes that are based on direct flux regulation, such as direct torque control or direct flux vector control. The maximum efficiency per torque (MEPT) stator flux map is computed offline using the traditional no-load and short-circuit tests' data. This strategy makes the motor efficiency is significantly improved below rated torque compared to the constant rated flux operation An iron loss model based on the stator flux and frequency is also proposed for the calibration of the machine loss model and also for on-line monitoring of the iron losses during motor.

Key Words — Direct torque control (DTC), Model predictive torque control (MPTC), Maximum Efficiency Per Torque (MEPT) operation of induction motor drives using Direct Flux Vector Control (DFVC)

1. INTRODUCTION

Using of efficient electrical drives enables to save energy. this goal can be fulfilled by using more efficient electrical machines or by employing optimal control techniques. The induction machine (IM) is undoubtedly known as the workhorse of the industry, due to this rigidness, simple and consolidated technology and low cost during the last decade, the IM has been replaced in many Adjustable Speed Drives (ASD) by Permanent Magnet (PM) motor since the PM machines have better efficiency and higher torque density. However, the price of high performance magnetising increased a lot during the last years, resulting in an important increase of the PM motors cost respect to several years ago. Due to their robustness and low cost, the induction motors can still be a valid solution for ASDs. At below base speed operation, particularly at lighter loads, certain optimisation control techniques are needed to improve the efficiency of IM drives. One of the techniques to improve efficiency is Flux Adaptation according to the load demand. The flux adaptation is categorized into 3 loss minimizing strategies. They are:

A. Control of a single motor variable:

The variables are displacement power factor control or the slip frequency control. Both of these are suitable for scalar control or vector control that is usually implemented in practice indirectly by regulation of current in rotor flux frame. In the slip frequency control, certain motor parameters are need meanwhile the need of these parameters is not required in displacement power factor control.

B. Search control:

Search control is also one of the loss minimising strategy in which input power is minimised through iterative adoption of motor flux. Direct measuring of power input is the basis for solution. There is no need of motor parameters in order to obtain the solution. The main drawback of this control strategy is particularly for drives requiring faster dynamics, the convergence is very slow. The motor may also get pull out if the load increases rapidly

C. .Loss model based control strategy:

This model is inherently best for vector controls as compared with scalar model. Hence certain motor parameters are considered since this strategy is suitable for vector control. The control strategy is mainly based on load model of motor or the power converter.

2. MODEL BASED LOSS MINIMIZATION

A. Induction Machine Model:

The machine modeling and control of induction motor with the reference frames are defined in Fig.1 as follows: stationary frame (α,β), rotor frame (d_m, q_m), rotor flux frame (*d,q*) and stationary flux frame (d_s,q_s). In general notation of the machine stator vectors (voltage, flux, current) will be called $\bar{v}$, $\bar{\lambda}$ and $\bar{\imath}$, and the subscript "*s*" will refer to the stator flux reference frame.

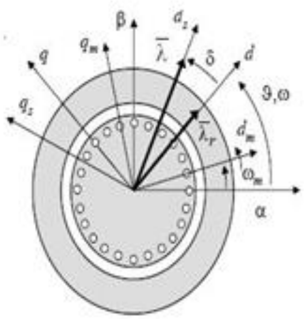

Fig.1. Reference frame of IM modeling and control

Where *Rs* is the stator resistance, ω is the synchronous speed, *p* is the number of pole-pairs, λ is the flux magnitude and δ is the load angle, i.e. the phase angle of the stator flux with respect to the rotor flux as shown in Fig.1.

The steady-state model used for the loss minimising technique represented in (d,q) rotor flux reference frame is shown in Fig.2.

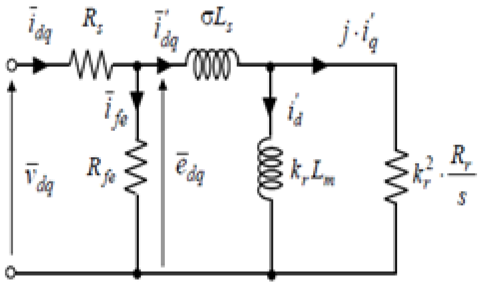

Fig.2. steady state equivalent circuit of IM in (d,q) rotor flux frame

The parameters in the steady state equivalent circuit are s is the slip, σ is the leakage factor, L_s is the stator inductance, L_m is the stator inductance, L_r is the rotor inductance and $k_r = \frac{L_m}{L_r}$ is the rotor coupling factor. The joule losses are determined by the stator resistance R_s and the rotor resistance R_r. The core losses are determined by the iron loss resistance R_{fe} which is connected in parallel with the stator branch. The stray load losses, the mechanical losses and the additional losses due to inverter supply are neglected.

Current to flux relationship of the induction magnetic model is represented with the following equations as

$$\bar{\lambda} = L_s.\bar{\imath}' + L_m.\bar{\imath}_r = L_{ls}.\bar{\imath}' + L_m.\bar{\imath}_m \quad (1)$$

$$\bar{\lambda}_r = L_m.\bar{\imath}' + L_r.\bar{\imath}_r = L_m.\bar{\imath}_m + L_{lr}.\,\bar{\imath}_r \quad (2)$$

Here L_{ls} , L_{lr} are the stator and rotor leakage inductances respectively. $\bar{\lambda}_m$ is the magnetizing flux vector. $\bar{\imath}_m$ is the magnetizing current vector.

The saturation is taken consideration in the magnetic model by the change of the magnetizing inductance with the magnetizing current.

In (d,q) rotor flux frame, the relationship between the stator flux and current vector components is

$$\begin{cases} i_{rd} = 0 \\ i_{rq} = -k_r\,.\,i_q^{'} \end{cases} , \quad \begin{cases} \lambda_d = L_s\,.\,i_d^{'} \\ \lambda_q = \sigma L_s.\,i_q^{'} \end{cases} ,$$

$$\begin{cases} \lambda_{rd} = L_m\,.\,i_d^{'} = \lambda_r \\ \lambda_{rq} = 0 \end{cases} \quad (3)$$

The voltage equation in this frame is

$$\bar{v}_{dq} = R_s.\bar{\imath}_{dq} + \bar{e}_{dq} = R_s.\bar{\imath}_{dq} + j.\omega.\bar{\lambda} \quad (4)$$

where $\bar{\imath}_{dq} = \bar{\imath}'_{dq} + \bar{\imath}_{fe} = \bar{\imath}'_{dq} + \frac{\bar{e}_{dq}}{R_{fe}}$

The electromagnetic torque, the synchronous speed and the slip speed equations are given a

$$T = \tfrac{3}{2}p\big(\lambda_d i'_q - \lambda_q i'_d\big) = \tfrac{3}{2}p(1-\sigma)L_s i_d^{'} i_q^{'} \quad (5)$$

$$\omega = \omega_m + \omega_{slip} = \omega_m + s.\omega \quad (6)$$

$$\omega_{slip} = \frac{i_q^{'}}{\tau_r\,.\,i_d^{'}}$$

where $\tau_r = L_r/R_r$ and $\sigma = 1 - L_m^2/L_r^2$

Vector diagram of the magnetic model of induction motor at steady state operating conditions is represented in Fig.3 as

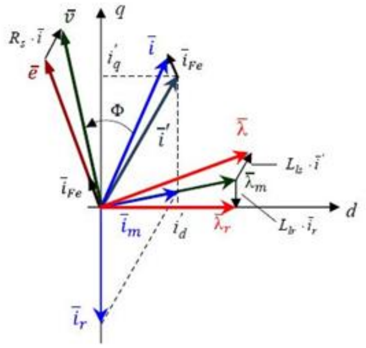

Fig.3. Vector diagram in rotor flux frame at steady state operation

The magnetizing current vector magnitude is identical to the d-axis component of the stator current vector downstream the iron loss resistance as

$$|\bar{\imath}_m| \cong i_d^{'} \quad (7)$$

B. Loss Model:

The machine losses then include only the stator and rotor Joule (ohmic) losses and the iron losses due to the fundamental flux components are depicted as

$$P_j = \frac{3}{2}.R_s.\left|\bar{\imath}_{dq}\right|^2 + \frac{3}{2}.k_r^2.R_r.i_q^{'2} \quad (8)$$

$$P_{fe} = \frac{3}{2}.\frac{\left|\bar{e}_{dq}\right|^2}{R_{fe}} = \frac{3}{2}.\frac{(\omega.\lambda)^2}{R_{fe}} \quad (9)$$

$$P_{loss} = P_j + P_{fe} \quad (10)$$

The IM efficiency is given as

$$\eta = \frac{P_m}{\frac{3}{2}.\left|\bar{v}_{dq}\right|.\left|\bar{\imath}_{dq}\right|.\cos(\Phi)} = \frac{P_m}{P_m + P_{loss}} \quad (11)$$

where $P_m = T.(\omega_m / \mathrm{p})$ is the mechanical power.

3. MODELING AND ESTIMATION OF IRON LOSSES

Hysteresis losses and eddy current losses are the significant iron loss considered in the modeling of induction machine.

P_{Hy} is the loss due to magnetic Hysteresis and is termed as

$$P_{Hy} = \chi.V.f.B_{max}^n \quad (12)$$

Here, V is the total core volume, f is the operating frequency, B_{max} is the peak flux density, η and χ are dependent constants of core material.

Introducing a constant k_{Hy} with A being the area of magnetic flux path and N being the number of winding turns, the geometric dimensions related terms are lumped into this constant.

$$k_{Hy} = \frac{\chi.V}{N.\ A^n} \quad (13)$$

$$P_{Hy} = k_{Hy}.f.\lambda^n \quad (14)$$

Where A is area of magnetic flux path , N is the number of winding turns, V is the total core volume, χ is the dependent constant, n ranges from 1.5 to 2.5 for generally used core materials.

P_{EC} is the eddy current loss and is termed as

$$P_{EC} = \frac{V.\pi^2.d^2.f^2.B_{max}^2}{6.\rho} \quad (15)$$

where d is the lamination thickness, ρ is the specific resistivity of the magnetic material.

Introducing a constant k_{EC}, the eddy current loss is given as

$$P_{EC} = k_{EC}.f^2.\lambda^2 \quad (16)$$

$$\text{where } k_{EC} = \frac{V.\pi^2.d^2}{6.\rho.N^2.A^2} \quad (17)$$

The total iron loss of the adjustable speed induction motor drives is given by

$$P_{fe} = P_{Hy} + P_{EC} = k_{Hy} f \lambda^n + k_{EC} f^2 \lambda^2 \quad (18)$$

The iron loss coefficients k_{Hy}, k_{EC} and the exponent term n are computed from experimental tests at different frequencies.

4. MAXIMUM EFFICIENCY PER TORQUE STATOR FLUX COMPUTATION

The objective of the proposed MEPT technique is to obtain an optimal stator flux which represents to the maximum motor efficiency. The optimal stator flux λ_{MEPT} is computated offline using an iterative computer based computation procedure as follows:

Required Motor Parameters:

The required motor parameters are the machine inductances (L_{ls}, L_{lr} *and* L_m), the machine stator and rotor resistances (R_s, R_r) and the iron loss Resistance R_{se}. The parameters are evaluated using the no-load and locked rotor tests at a specific temperature. The magnetising current magnitude can be inferred with the I_j^I current component. The maximum magnetising current from the no-load test will be the maximum allowed d axis current I_{dmax}.

Current mapping in rotor flux frame and computation of machine model:

As per the overload current limit it needs the maximum machine current I_{max} as input. i' (m, n) vector is represented as

$$\bar{i}\,(m, n) = I(m).e^{j\vartheta(n)} = i'_d(m, n) + j.i'_q(m, n) \qquad (19)$$

Mapping of ī' in (d,q) rotor flux frame

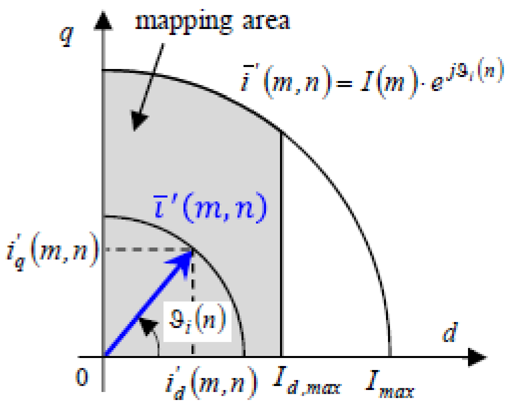

Fig.4. mapping of ī (m, n) in (d,q) rotor flux frame

In this current mapping model, current position ranges between a minimum value and 90 electrical degrees and stator current magnitude ranges between zero and I_{max} . The minimum value is not constant and it is chosen to avoid having a d-axis current higher than I_{dmax} .

Optimal stator flux computation :

Optimal stator flux can be computated using MTPA technique and MEPT technique. In MTPA technique, it selects the flux $\lambda_{MTPA}(m)$ that relates to maximum torque where as in MEPT technique, it selects the flux $\lambda_{MEPT}(m)$ that relates to maximum efficiency.

5. DIRECT FLUX VECTOR CONTROL STRATEGY

The Induction Motor control scheme is shown in below Fig.3 for a speed controlled drive. This control scheme can also be used in torque mode DFVC control scheme utilises flux and current regulation using simple Proportional Integral (PI) controller applied in (d_s, q_s) stator flux frame.

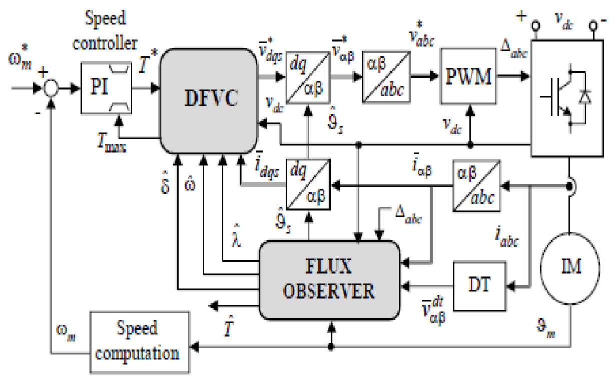

Fig.5. IM control scheme with direct flux vector control

Combination of the advantages of direct flux regulation as for Direct Torque Control and current regulation as for field oriented control scheme is used on a hybrid control scheme in DFVC.

In this scheme without the interference of q_s axis, the stator flux is directly controlled by the d_s axis voltage. Being set forth by the proportional gain of the PI flux controller, the flux 100p bandwidth can be very high. Controlling the q_s axis current component using a Pi current controller whose output is q_s axis voltage, the regulation of torque is done. With the proportional gain of the PI current controller and inductance L_s, the bandwidth of the q_s axis current loop is obliged.

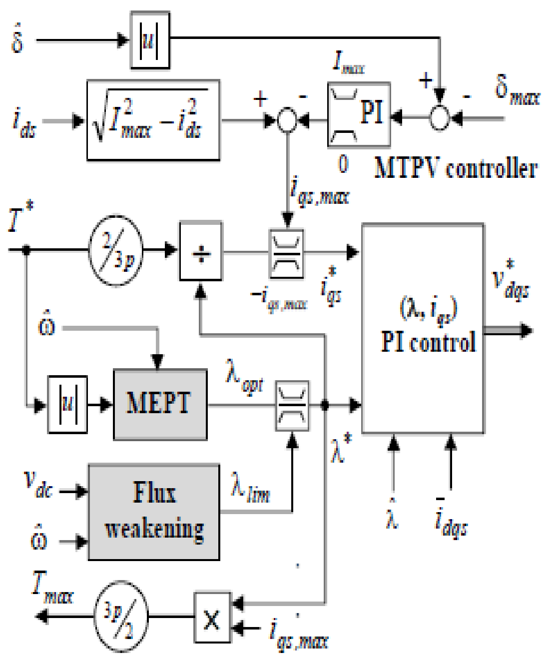

Fig.6. Direct flux vector controller with MEPT for reference flux generation according to the torque command.

With the inputs of the torque demand and motor speed the reference flux is provided by an MEPT block as shown in Fig.6 to produce the optimal flux reference for maximum efficiency.

The proposed MEPT technique is to obtain an optimal stator flux which represents to the maximum motor efficiency. The optimal stator flux λ_{MEPT} is computated offline using an iterative computer based computation. The efficiency improvement is done precisely below the rated torque, independently of motor operating speed.

6. SIMULATION RESULTS

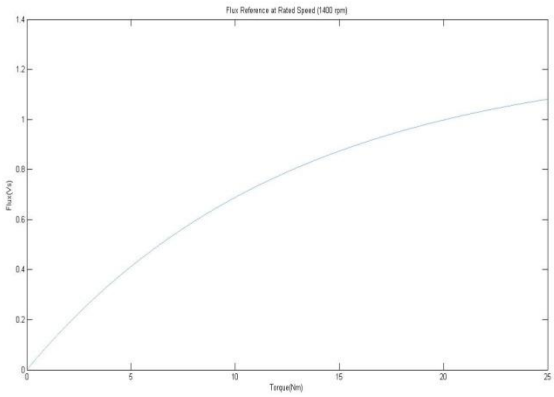

Fig.8. Simulation results of flux reference on y-axis and torque on x-axis at 1400rpm

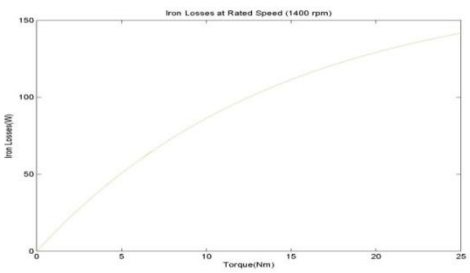

Fig.9. Simulation results of iron losses on y-axis and torque on x-axis at 1400rpm

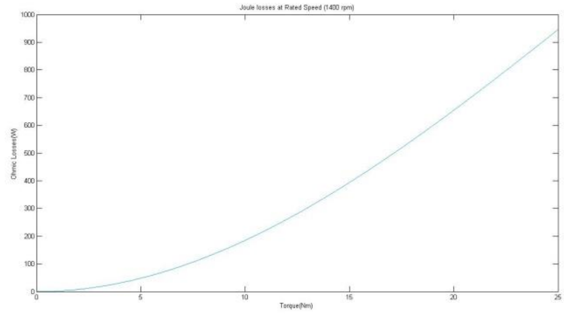

Fig.10. Simulation results of joule losses on y-axis and torque on x-axis at 1400rpm

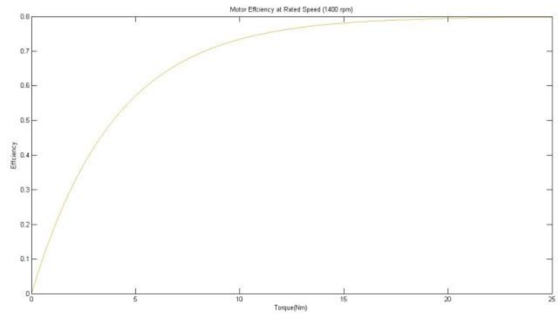

Fig.12. Simulation results of efficiency on y-axis and torque on x-axis at 1400rpm

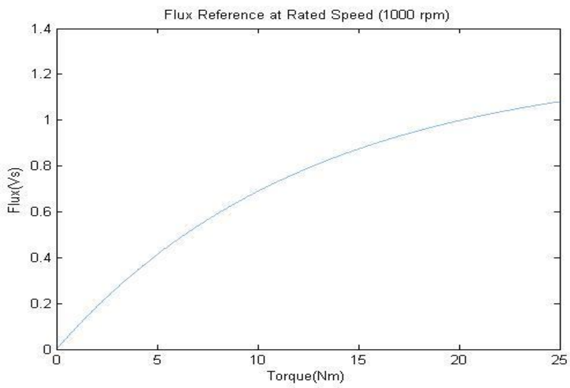

Fig.13. Simulation results of flux reference on y-axis and torque on x-axis at 1000rpm

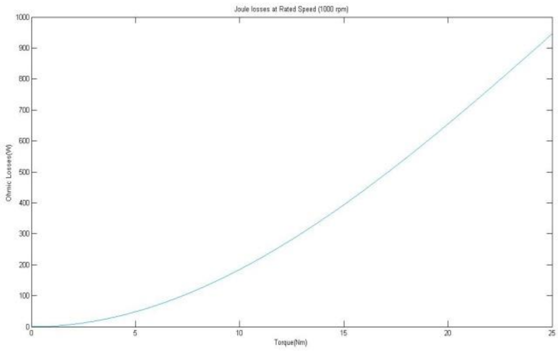

Fig.14. Simulation results of joule losses on y-axis and torque on x-axis at 1000rpm

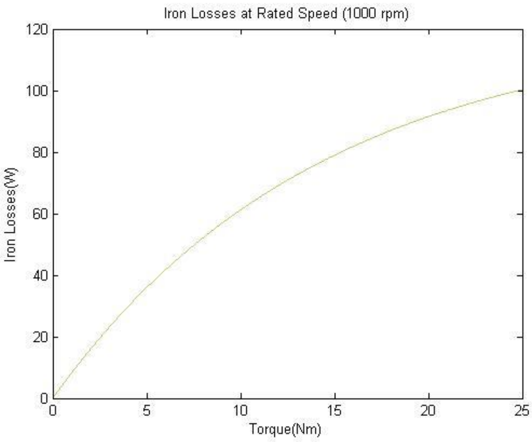

Fig.15. Simulation results of Iron losses on y-axis and torque on x-axis at 1000rpm

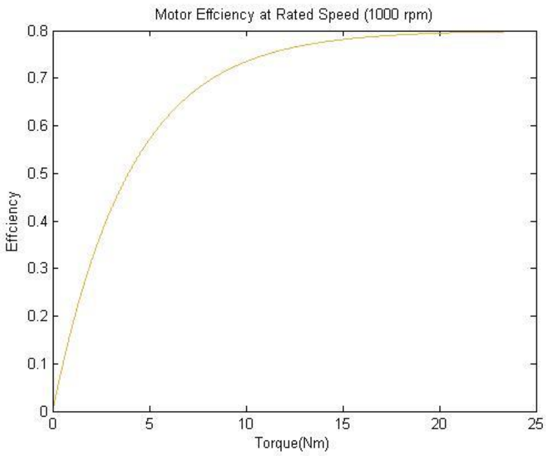

Fig.16. Simulation results of efficiency on y-axis and torque on x-axis at 1000rpm

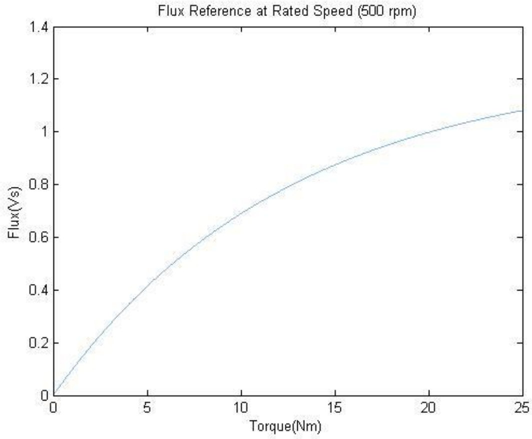

Fig.17. Simulation results of flux reference on y-axis and torque on x-axis at 500rpm

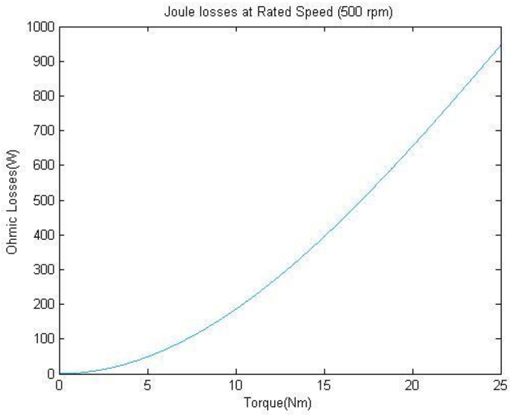

Fig.18. Simulation results of joule losses on y-axis and torque on x-axis at 500rpm

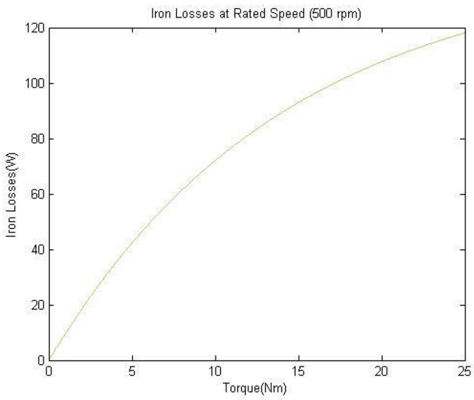

Fig.19. Simulation results of Iron losses on y-axis and torque on x-axis at 500rpm

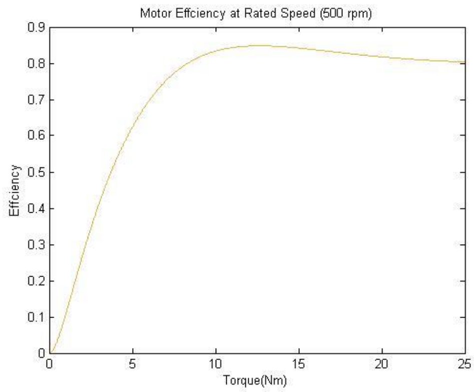

Fig.20. Simulation results of flux reference on y-axis and torque on x-axis at 1400rpm

With the MEPT technique the efficiency improvement is significant at loads below the rated torque, independently of the motor operating speed.

7. Appendix

The IM rated data and parameters are: rated power 2.2 kW, rated voltage 400V, rated current 5.08A, rated frequency 50Hz, rated speed 1400rpm, rated torque 15 Nm, R_s = 3.37 (25C), R_r= 2.2 (25C), L_{ls} = L_{lr} = 16 mH.

8. CONCLUSION

This paper presents a map-based stator flux reference computation for Direct Flux Vector Control Induction Motor Drives. The results are a LVT having as input only the torque demand. MEPT flux is obtained as an interpolation according to torque demand and rotor speed. The proposed MEPT flux computation takes into account the core losses at that flux level. Experimental results, including MEPT and efficiency validation and torque transient performance are presented for a 2.2 kw IM. The results show that at below rated speeds the motor efficiency is significantly improved compared with the constant rated flux operation.

REFERENCES

[1] Y. Zhang and J. Zhu, "A novel duty cycle control strategy to reduce both torque and flux ripples for DTC of permanent magnet synchronous motordrives with switching frequency reduction," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 3055–3067, Oct. 2011..

[2] J. Beerten, J. Verveckken, and J. Driesen, "Predictive direct torque control for flux and torque ripple reduction," *IEEE Trans. Ind. Electron.*, vol. 57, no. 1, pp. 404–412, Jan. 2010.

[3] S. A. Davari, D. A. Khaburi, F. Wang, and R. M. Kennel, "Using full order and reduced order observers for robust sensorless predictive torque control of induction motors," *IEEE Trans. Power Electron.*, vol. 27, no. 7, pp. 3424–3433, Jul. 2012.

[4] C. A. Rojas, J. Rodriguez, F. Villarroel, J. R. Espinoza, C. A. Silva, and M. Trincado, "Predictive torque and flux control without weighting factors," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 681–690, Feb. 2013.

[5] Y. Zhang, W. Xie, Z. Li, and Y. Zhang, "Model predictive direct power control of a PWM rectifier with duty cycle optimization," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5343–5351, 2013.

[6] H. Miranda, P. Cortes, J. Yuz, and J. Rodriguez, "Predictive torque control of induction machines based on state-space models," *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 1916–1924, Jun. 2009.

[7] Y. Zhang and H.Yang, "Torque ripple reduction of model predictive torque control of induction motor drives," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013, pp. 1176–1183.

[8] M. Nemec, D. Nedeljkovic, and V. Ambrozic, "Predictive torque control of induction machines using immediate flux control," *IEEE Trans. Ind.Electron.*, vol. 54, no. 4, pp. 2009–2017, Aug. 2007.

[9] B. Kenny and R. Lorenz, "Stator- and rotor-flux-based deadbeat direct torque control of induction machines," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 1093–1101, Jul./Aug. 2003.

[10] P. Cortes, J. Rodriguez, C. Silva, and A. Flores, "Delay compensation in model predictive current control of a three-phase inverter," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 1323–1325, Feb. 2012.