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Full Length Article

An improved algorithm for direct computation of optimal voltage and frequency for induction motors

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A B S T R A C T

Owing to the constant v/f operation of induction motors which are commonly employed in conveyor belt drives, the core and copper losses are generally high. The load cycles of the drives are mostly limited to light and medium load conditions with full speed range. Hence any effort to minimize the losses can bring significant savings in energy and therefore in running costs. In this paper a unique loss minimization algorithm is proposed for an Induction Motor Drive (IMD) whereby the input voltage and frequency of the motor are optimized to minimize the total losses. The proposed algorithm is based on the steady state model of induction machine. Hence the analysis and the applications are restricted to steady state operating conditions. A comprehensive analysis of the drive performance under different operating conditions and a Loss Minimization Control (LMC) algorithm for the determination of the optimal input voltage and frequency are presented. Further, a comparison of steady state performance of the proposed LMC and that with the Field Oriented Control (FOC) is carried out. Results of MATLAB simulations and laboratory tests on the drive under study reveal that the drive efficiency is increased, especially at light load condition.

1. Introduction

Conveyor belt drives employing multiple motors play an important role in bulk material transportation in industrial applications, power plants etc. Induction motors of megawatt rating with high slip characteristics are commonly used for driving the conveyor belts. The drive needs to run continuously with all the motors irrespective of the load conditions. A major challenge in induction motor drives is to make it energy efficient. The copper loss and core loss constitute the primary losses in an induction motor. While the copper losses vary with load, core losses are predominant at light loads due to the rated flux operation. The high slip characteristics and long hours of low power operation of conveyor motors lead to low efficiencies. Most commonly used speed control methods of IMs are v/f scalar control, vector control and direct torque control. The scalar v/f speed control method is dominantly used in most of the industrial applications where the flux is kept constant for speeds below the base speed, as the stator flux is a function of stator v/f ratio. Rated flux operation of induction motor irrespective of load and speed also contributes to significant power loss in the drive.

A number of techniques have been suggested for efficiency optimization through flux regulation of induction motors at light loads. They are broadly categorized into Search Controller (SC) and Loss Model Controller techniques. Search Control [1–7] methods continuously measure the input power to the motor, by varying the flux level in small steps until the input power is minimum for the given operating speed and load. The advantage of SC is that it does not require speed and torque estimation. A fast converging SC using golden section technique combining indirect FOC [2] is proposed to eliminate the torque pulsations by incorporating a low pass filter. Another study [3] put forward two efficiency optimization controls for vector controlled IMD - one is a ramp search method and the other is a hybrid method combining benefits of both SC & model control. A scalar controlled loss minimization scheme with stator current as controlled variable for SC is discussed in [4]. The paper [8] discusses an algorithm for speed estimation by spectral power search for wound rotor induction motor by monitoring supply frequency. A speed sensor-less vector controlled flux optimizing scheme, incorporating iron losses and magnetic saturation is proposed in [9]. Loss Model based control method utilizes the model of the system losses to compute the

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Nomenclature

i_s, i_r	stator and rotor currents per phase, A
L_{ls}, L_{lr}	stator and rotor winding inductances per phase, H
L_m	magnetizing branch inductance per phase, H
P_m	motor mechanical power output, Watt
P_{em}	electromagnetic power developed, Watt
R_Ss, R_r	per phase resistance of stator and rotor windings, ohm
R_m	equivalent iron loss resistance per phase, ohm
V_s	stator voltage per phase, V
s	slip, p.u.
ω_r	angular speed (electrical) of rotor, rad/s
ω_s	angular speed (electrical) of stator supply, rad/s
J	moment of inertia, kg.m^2
F_m	total motional resistances in top run/return run in a steady state operation, N
v	belt speed (m/s)

optimum flux for a given load and speed. The main advantage of the Model control based algorithm over SC is that it converges fast and does not cause torque pulsations. Model control entails use of accurate machine parameters for the computation of losses and to select optimum flux level that minimizes the total copper losses [10]. In [11], the model controller and Adaptive-Back stepping-based Nonlinear Controller (ABNC) are combined together for vector controlled induction motor drive for a high dynamic performance and high efficiency. Online parameter estimation for Model control is carried out with ABNC so that the effect of parameter deviations can be overcome. Another Model control based study [12] proposed a strategy for maximum efficiency per torque (MEPT) in which the optimal stator flux is computed offline and implemented as look up table. A vector controlled on-line efficiency optimization scheme [13] involves the regulation of the magnetizing current by measuring the input power alone. Reference [14] suggests the regenerative power control for extended ride through capability of vector controlled drive via electrical loss minimization. In [7] the author proposed a flux weakening technique known as Perturbing Rotor Frequency (PRF) without the need of the machine parameters. In [15], a flux weakening scheme for induction motor drive using adaptive PI controller for speed loop is described. In [16], a state space model of IM combining model controller, hybrid FOC-DTC and an extended Kalman filter observer for speed estimation for efficiency enhancement is put forth.

A boost converter with diode bridge rectifier of VFD resulted in controlled dc bus voltage, improved line current waveform, power factor and efficiency [17]. An online loss minimization based on predictive control considering the torque transient power losses is discussed in [18]. A comparison of efficiency of induction machines (IMs) and interior permanent-magnet synchronous machines (IPMSMs) is presented in [19]. With loss minimization control, the efficiency of IM is comparable to that of IPMSM.

In this paper a Loss Minimization Control (LMC) algorithm is developed considering the total losses of the induction machine which is a function of the winding currents and the flux which in turn depends on the applied voltage and frequency. In the proposed LMC algorithm, the optimal values of slip and applied voltage at a given mechanical power and speed are determined analytically by measuring speed. Further, certain maximum limits on the applied voltage magnitude and frequency are imposed so that the machine is not subjected to abnormal voltage, frequency or flux. The study presents a comprehensive analysis along with the results of simulations of the test set up in MATLAB. Also tests are conducted on a laboratory machine to verify the proposed algorithm. The close agreement between the simulations and the experimental results confirms the effectiveness of the proposed algorithm. Section 2 describes the loss minimization control algorithm. Closed loop implementation of the algorithm is discussed in Section 3 whereas Sections 4 and 5 presents the results of simulations and the experiments.

2. System description

During low power operation, the iron loss and total copper loss are reduced significantly by reducing the flux, as iron loss is proportional to the magnitude of flux. In this context, a simple LMC algorithm is proposed in which the total loss of a squirrel cage induction motor is minimized. The stator supply frequency and voltage magnitude for inverter fed SCIM is computed with the scalar LMC based algorithm which does not entail rotor flux angle information.

2.1. Steady state analysis of induction motor considering core losses

Fig. 1 shows the diagram of per phase equivalent circuit of a caged rotor induction motor referred to the stator.

This section discusses a new scheme for predetermining the induction motor performance.

For a known load power and speed the rotor current can be expressed as,

$$i_r = \sqrt{\frac{sP_m}{3R_r(1-s)}} \tag{1}$$

where, slip '*s*' is given by,

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{2}$$

The expression for voltage across magnetizing branch is,

$$E = \left(\frac{R_r}{s} + j\omega_s L_{lr}\right) * i_r \tag{3}$$

Magnetizing and core loss component currents are respectively are

$$i_m = \frac{E}{j\omega_s L_m} \tag{4}$$

And

$$i_f = E/R_m \tag{5}$$

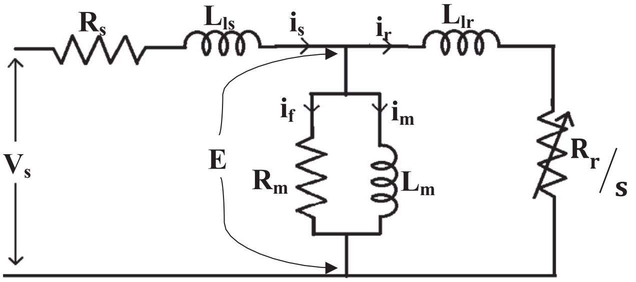

Fig. 1. Induction machine per phase equivalent circuit.

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