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Direct torque control implementation with losses minimization of induction motor for electric vehicle applications with high operating life of the battery

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ABSTRACT

In recent years, the electric vehicle (EV) motorization control takes a considerable interest of industrials. This paper, introduces a new approach to the direct torque control (DTC) with loss minimization of induction machine (IM) drive which is proposed for EV applications. The purpose of this work is to take advantages of the strengths of both techniques DTC and optimal control, the new approach is called: optimal direct torque control (ODTC). Simulation and experimental results obtained show that the losses have been reduced by this method, since the flux varies depending on the load (operating point) and the current consumed by the machine is reduced therefore, the current delivered by the battery was reduced especially during acceleration and deceleration periods it would increase battery life and prevent its discharge. For this the proposed ODTC appears to be very convenient for EV.

Introduction

Nowadays the oil resources are becoming exhausted and in addition the rate of pollution reaches alarming levels due to emissions from combustion engines. The automotive technology provided by electric energy that is treated as a non-polluting energy is considered as a solution. An electric vehicle (EV) uses one or more electric motors for propulsion powered by rechargeable battery packs. EVs have several advantages over vehicles with internal combustion engines and constitute a possible alternative to conventional vehicles [1,2]. Many different types of energy storage technologies are under development, batteries are currently used as the main source of electric power in the EV. The battery should have a good ability of energy storage, offer high energy efficiency, high current discharge, capability to charge empty cells during regenerative braking forces, and high cycle life [3,4]. The application of induction motors in traction systems, including electric vehicles, takes a great interest of industrials [5]. Using electric motors efficient, electric vehicles provide the means to achieve a clean and efficient urban transport system and a friendly environment. Induction motors have good efficiencies when operating at steady state and rated load [6]. In the case of variable speed operating, they normally operate at rated flux in a variable frequency

Abbreviations: IM, induction motors; DTC, direct torque control; LMC, minimum loss model controller; ODTC, optimal direct torque control; EV, electric vehicle; SOC, state of charge.

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Nomenclature

V_{ds}, V_{qs}	two-phase stator voltages, V
V_{dr}, V_{qr}	two-phase rotor voltages, V
i_{ds}, i_{qs}	two-phase stator current, A
i_{dr}, i_{qr}	two-phase rotor current, A
J	inertia moment, Kg m^2
M	mutual inductance, H
$L_s = L_r$	stator (rotor)self-inductance, H
P	number of pole pairs
C_r	load torque, Nm
f	viscous friction coefficient, N m s
R_s,R_r	stator, rotor resistances, Ω
R_{fs}	equivalent stator iron loss resistance, Ω
R_{fr}	equivalent rotor iron loss resistance, Ω
T_e	electromagnetic torque, Nm
P_{loss}	total losses, Watt
P_{cs}	stator core losses, Watt
P_{cr}	rotor core losses, Watt
P_{cl}	total core losses, Watt
P_{scl}	stator copper losses, Watt
P_{rcl}	rotor copper losses, Watt
E_{batt}	voltage source, V
R_{batt}	internal battery resistance, Ω
I_{batt}	battery current, A
C_{10}	rated capacity, F

Greek letters

$\varphi_{s\alpha}$,$\varphi_{s\beta}$	flux components along α and β stator axes, Wb
φ_{ds}, φ_{qs}	two-phase stator fluxes, Wb
φ_{dr}, φ_{qr}	two-phase rotor fluxes, Wb
φ_{ropt}, φ_{sopt}	optimal rotor and stator flux, Wb
ω_s, ω_r	stator and rotor angular velocities, rad/s
σ	total leakage factor
σr	rotor leakage factor

drive to obtain the best transient response. Different approaches have already been proposed to improve the induction motor efficiency especially under low load conditions [7]. A first approach is based on modelling of the motor and losses to derive an objective function for yield the maximum efficiency. Thus, this method is a feed forward approach that treats the situation analytically by modelling the losses and is termed as "Loss Model Controller" (LMC). A second method is of a feedback nature that finds the maximum efficiency by adopting a search technique and is called "Search Controller" [8]. Besides, field oriented control (FOC) methods provide good dynamic and stationary performances in the case of induction drives but they generally don't take in consideration the loss minimization. Thus, adding LMC to FOC is one of the strategies that lead to energy saving. However, FOC needs a very accurate knowledge of the machine model parameters as well as high computational requirement due to the use of the coordinate transformation [9]. The basic concept of DTC is to control both stator flux and electromagnetic torque of the machine simultaneously by using a switching vector look-up table [10,11]. Based on stator flux and torque estimations, it has many advantages, compared to field oriented control, such as less machine parameter dependence, does not require coordinate transformation and any current regulator, simpler implementation and quicker torque response [12]. However, DTC presents some drawbacks: difficulty to control torque and flux at very low speeds, high current ripple causing high torque ripple and variable switching frequency behaviour [13].

The purpose of this paper is to offer an alternative to the classical LMC control by the combination of this last with the direct torque control scheme. The proposed approach is called Optimal Direct Torque Control and it appears to be very convenient for EV applications. For this the proposed ODTC was used to minimize the induction motor losses in order to estimate the optimal magnetizing flux, therefore maximizing the efficiency and increasing the running distance per battery charge. This leads to energy saving in a wide operating range while benefiting from the direct torque control advantages in terms of implementation simplicity and high dynamics. The simulation is given under Matlab/Simulink, and the obtained results are compared to the experimental ones obtained using an experimental bench in our laboratory LTII.

Direct torque control strategy

DTC method uses a simple switching table to identify the most suitable inverter state to achieve a desired output torque. The algorithm, based on the flux and torque hysteresis controllers, determines the voltage needed to drive the flux and torque to the desired values [14]. These hysteresis controllers maintain the flux and torque within an allowed upper and lower limit.

Basic direct torque control for IM

From the model of the machine expressed in a reference frame linked to the stator, the stator flux vector is estimated from the following relationship:

$$\vec{\varphi}_s(t) = \int_0^t \left(\vec{V}_s(t) - R_s \vec{i}_s(t)\right)dt \tag{1}$$

The stator flux components $\phi_{s\alpha}$ and $\phi_{s\beta}$ can be estimated by:

$$\begin{cases} \varphi_{s\alpha}(t) = \int (V_{s\alpha}(t) - R_s \cdot i_{s\alpha}(t))dt \\ \varphi_{s\beta}(t) = \int (V_{s\beta}(t) - R_s \cdot i_{s\beta}(t))dt \end{cases} \tag{2}$$

where: $V_{s\alpha}$, $V_{s\beta}$, $i_{s\alpha}$ and $i_{s\beta}$ are stator voltages and currents along α and β stator axes respectively.

The magnitude of the stator flux can then be estimated by:

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \tag{3}$$

The phase angle of the stator *flux* can be calculated by:

$$\theta_s = \tan^{-1}\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \tag{4}$$

And the electromagnetic torque can be estimated by: