Energy 89 (2015) 55–64

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Analytical solution of optimized energy consumption of Double Star Induction Motor operating in transient regime using a Hamilton–Jacobi–Bellman equation

Imen Kortas*, Anis Sakly, Mohamed Faouzi Mimouni

Research Unit of Industrial Systems Study and Renewable Energy (ESIER), National Engineering School of Monastir (ENIM), Ibn El Jazzar, Skaness, 5019, Monastir, University of Monastir, Tunisia

ARTICLE INFO

Article history:
Received 4 February 2015
Received in revised form
22 June 2015
Accepted 10 July 2015
Available online 6 August 2015

Keywords:
Double Star Induction Machine
Rotor Field Oriented Control
Hamilton–Jacobi–Bellman
Optimal control
Energy minimization

ABSTRACT

The problem of energy optimization of a DSIM (Double Stator Induction Motor) using the concept of a RFOC (Rotor Field Oriented Control) can be treated by an OCS (Optimal Control Strategy). Using OCS, a cost-to-go function can be minimized and subjected to the motor dynamic equations and boundary constraints in order to find rotor flux optimal trajectories. This cost-to go function consists of a linear combination of magnetic power, copper loss, and mechanical power. The dynamic equations are represented by using a reduced Blondel Park model of the DSIM. From the HJB (Hamilton–Jacobi–Bellman) equation, a system of nonlinear differential equations is obtained, and analytical solutions of these equations are achieved so as to obtain a time-varying expression of a minimum-energy rotor flux. This analytical solution of rotor flux achieved maximum DSIM's efficiency and was implemented in the ORFOC (optimal rotor flux oriented control) and compared to the conventional RFOC at different dynamic regime of the DSIM. Simulation results are given and improved the effectiveness of the proposed strategy.

1. Introduction

Some of the largest opportunities to save energy and reduce operating costs in buildings and industrial facilities come from optimizing electric motor systems. In general, the most part of electricity assumed flows through motors mainly induction motors [13]. The DSIM (Double Stator Induction Motor) is the dominant technology used today due to its high performance, its high reliability, and its speed and torque capabilities. In many electrical drive applications, the Double Star Induction Motor does not operate at the nominal point since the desired torque may change according to position or velocity. It is then interesting to consider other flux operation modes in order to optimize the system performance, particularly when the task is to reduce the DSIM energy consumption under transient modes. In the industrial applications, many electrical drives operate with a rapidly-varying load torque [15]. The transient regime is explained by nonlinear models that require robust algorithms of energy minimization strategies. To achieve performance, a strategy of optimizing energy of the DSIM in transitory regime using calculus of variation theory is developed. An integral function is considered and decomposed into a weighted sum of power-energy of the DSIM for a given time interval. This function called the cost function will be constrained to boundaries conditions and to rotor flux and motor speed dynamical equations which are developed from the DSIM transient model in a turning (d,q) reference frame [1]. However, the variational calculation leads to solving a nonlinear differential equation which depends explicitly on the boundary conditions.

In this context; Lorenz et al. [2,3] have opted for an operating loss modeled by copper and core losses. In order to compute the minimal loss flux trajectory, they developed an optimal control strategy using a dynamic programming technique. C. Canudas de Wit et al. [4,5] considered a convex energy cost function including the stored magnetic energy and coil losses. They developed a nonlinear Euler–Lagrange equation from which an optimal flux norm trajectory can be derived. The obtained equation was unsolvable for an arbitrary torque. They proposed a suboptimal analytical solution aligned with a constant torque operation. In Ref. [6], the authors present the solution of the nonlinear optimal

* Corresponding author.
E-mail addresses: kortas.imen@yahoo.fr (I. Kortas), sakly_anis@yahoo.fr (A. Sakly), Mfaouzi.mimouni@enim.rnu.tn (M.F. Mimouni).

http://dx.doi.org/10.1016/j.energy.2015.07.035
0360-5442/

control problem of three–phase IM (induction motor). A third order nonlinear model described in arbitrary rotating frame of induction motor is used in this paper along with a quadratic performance index. The problem is solved using the quasilinearization approach which converts the nonlinear optimal control problem into sequence linear quadratic optimal control problems. In Ref. [7], a new minimum-time minimum-loss speed control algorithm for induction motors is suggested to obtain high performance, as well as high efficiency, under field-oriented control with practical constraints on voltage and current. This algorithm utilizes a two-stage control. In the transient stage, a maximum torque control algorithm is utilized to get the minimum-time response. In the steady state, a minimum-loss control algorithm is applied to improve the efficiency. Simulation studies show the performance of the proposed minimum-time minimum-loss control algorithm under field-oriented control.

S. M. Yang and F.C. Lin [8] propose a scheme that uses power factor control with automatic measurement of the minimum-loss power factor commands. A fuzzy logic compensator is included in the controller to improve the accuracy of the generated commands. The scheme is simple for implementation and does not require an a priori knowledge of motor parameters. Experimental results have validated the effectiveness of this scheme to minimize the motor operating losses. A design of an adaptive nonlinear control system for high performance induction motors is developed in Ref. [9]. The proposed control system is of the explicit model reference type. It consists of a nonlinear controller (inner loop) that controls the rotor speed, an adaptation mechanism (outer loop) that involves a maximum likelihood estimator, communicating with a feedback control law that uses the results of the adaptation mechanism to redesign the inner loop controller online. The advantage of synthesizing this type of controller lies in the fact that the desired trajectory of the rotor speed is determined from the output of the reference model, while the control trajectories that lead to that behavior are computed through the developed state feedback control law. The control system is simulated under a situation where some of the parameters vary in the presence of noise. It is shown that the adaptive controller keeps the performance of the drive system close to the desired performance even in the presence of uncertainty. The effect of measurement noise is also taken into consideration to show that the controller is feasible for practical situations.

M. H. Ahmadi et al. [16] present a developed ecological function for absorption refrigerators with four-temperature-level. Moreover, aforementioned absorption refrigerator is optimized by implementing ecological function. With the aim of the first and second laws of thermodynamics, an equivalent system is initially determined. To reach the addressed goal of this research, three objective functions that the COP (coefficient of performance), the ecological function and thermoeconomic criterion have been involved in optimization process simultaneously. Three objective functions are maximized at the same time. Developed MOEAs (multi objective evolutionary approaches) on the basis of Non-dominated Sorting Genetic Algorithm (NSGA-II) method are implemented throughout this work.

In Ref. [17], authors propose an ecological and thermal approaches for the Ericsson cryogenic refrigerator. Three objective functions (input power, coefficient of performance and ecological objective function) are gained for the suggested system. Throughout the current research, an EA (evolutionary algorithm) and thermodynamic analysis are employed to specify optimum values of the input power, coefficient of performance and ecological objective function of an Ericsson cryogenic refrigerator system. Four setups are assessed for optimization of the Ericsson cryogenic refrigerator. Throughout the three scenarios, a conventional single-objective optimization has been utilized distinctly with each objective function, nonetheless of other objectives. Throughout the last setting, input power, coefficient of performance and ecological function objectives are optimized concurrently employing a non-dominated sorting GA (genetic algorithm) named the non-dominated sorting genetic algorithm (NSGA-II). As in multi-objective optimization, an assortment of optimum results named the Pareto optimum frontiers are gained rather than a single ultimate optimum result gained via conventional single-objective optimization. Thus, a process of decision making has been utilized for choosing an ultimate optimum result.

In Ref. [18], an optimization investigations of an irreversible absorption heat pump system on the basis of a new thermo-ecological criterion is developed. The objective functions which considered are the specific heating load, *COP* (coefficient of performance) and the *ECOP* (ecological coefficient of performance). Three objective functions of the ECOP, COP and the specific heating load are optimized simultaneously using the multi-objective optimization algorithm NSGAII. *COP* and *ECOP* are maximized and specific heating load is minimized in order to get the best performance. Decision making is done by means of three methods of LINAMP and TOPSIS and FUZZY. Finally, sensitivity analysis and error analysis was performed for the system.

S. Hoseyn et al. [19] present an optimal design of a solar-driven heat engine Based on thermal and ecological criteria. In the present investigation, thermodynamic analysis and an EA (evolutionary algorithm) were employed to optimize the dimensionless ecological function, thermal efficiency, and dimensionless power of a solar-driven engine system. Four scenarios were conducted for optimization of the solar heat engine. In the first three, a traditional single objective optimization was employed separately with each objective function, regardless of other objectives. In the fourth scenario, efficiency and power objectives were optimized simultaneously using a nondominated sorting GA (genetic algorithm) called the nondominated sorting genetic algorithm (NSGA-II). As in multiobjective optimization, a set of optimal solutions called the Pareto optimal frontier was obtained instead of a single final optimal solution obtained in traditional single-objective optimization. Therefore, a process of decision making was employed for selecting a final optimal solution. Three decision-making procedures were applied to find optimized solutions from the Pareto optimal solutions in the objectives' space. The results obtained from four optimization scenarios were compared and discussed using a deviation index introduced in this paper. It was shown that the optimal results obtained in single-objective optimization with an ecological objective are very close to the corresponding results obtained in the multiobjective optimization, in that the power and thermal efficiency are optimized simultaneously.

In this paper, minimum energy control will be solved by an alternative approach called the HJB (Hamilton-Jacobi Bellman), in which the optimal control is not interested in the specific initial states, but in any unspecified initial conditions. In fact, the cost function subject to the criterion index is transformed into a cost-to-go function. By imposing a transient mode to the DSIM drive, the nonlinear HJB equation was successfully solved in an analytical form and offered a time-varying expression of minimum energy rotor flux. This analytical solution was implemented in an optimal RFOC (Rotor Field Oriented Control) in which both a deadbeat rotor flux controller and a saturation model are introduced.

This paper is organized as follows: Section 2 is mainly intended to describe the full DSIM model. Section 3 is devoted to present the reduced model. In the fourth section the energy model of the DSIM is explained. In Section 5, the optimal control strategy is presented in details by the energy-power cost function, the presentation of the optimal control problem, the mechanical system operation (the