Optimal control of induction machines under minimum energy in opencast mining machinery

Mining industry is one of the most important users of electric motors. The most commonly used in the contemporary mining industry is alternating current (AC) machines which are used for converting electrical energy into mechanical energy. This paper presents the solution of the nonlinear optimal control problems of three-phase induction mining machinery (IMM). A fifth order nonlinear model has been described in arbitrary rotating frame (d-q) of induction machine which is used in this paper along with a quadratic performance index (QPI). The problem has solved using the Taylor expansion about an operating point method which converts the nonlinear optimal control problem into sequence of linear quadratic optimal control problems. The control objective is to minimize the total energy, ensuring torque and speed tracking control requirements. The evaluation of a simulation for an electrical drive application shows that operation at varying optimal supply voltages (V_{dsopt}, V_{qsopt}) preserves well speed, torque and flux tracking performances, while increasing motor efficiency. The system is stable with the properly selected settings of optimal regulators, which are particularly applicable during the operation of machinery used in mining exploitations.

Keywords: *Mining industry, induction motors, minimization of energy, Riccati equations, torque and speed control.*

1. Introduction

The basic need for efficient use of energy imposes requirements of world law on the mining companies. Mining industry is one of the recipients of electric motors. Mining machinery for coal exploitation and mineral processing, machinery for mining and equipment for mineral raw materials, generally represent the industry in which development and manufacturing experience plays a considerable role (Pytel and Jaracz, 2012; Gumula and Pytel, 2014). Although DC motors are still widely used in draglines and shovels, for the purpose of this research paper, only three-phase AC machines will be addressed, particularly induction machines. Some machines work well at fixed speeds, such as mining conveyors, crushers and draglines. Control for these motors is focused on reliable, safe starting. In addition to controlling speed, you also have to consider torque requirements. Torque control focuses on providing adequate torque for the load at all operating points, and on protecting the equipment and people from excess torque and currents. Motor torque and motor current are roughly proportional (Paul and William, 2017).

Electrical machinery for mines usually consists of AC power consumers based on a squirrel cage induction motor such as exhauster fans, deep well pumps for pumping water out of mines, grinding machines for ore reduction, drilling machines, hoisting equipment, etc. (Linkov and Olizarenko, 2015). The main objective in conservation of electrical energy in mines includes replacement of conventional systems with the present technology system which leads to reduction in energy consumption per annum for about 10-15% (Ganapathi and Manjunath, 2016).

The consumption of both thermal and electrical energy is growing, no matter the political intentions, so sooner and later very large investments in transmissions lines and power stations are required. For the end-user there is of course the simple incentive that gets the same work done with less energy by using more efficient energy conversion processes (M. Shepard, 1992).

Induction motors are also attractive in new electric generation shops, water pumps and electric transportation systems (Abrahamsen, 1997). These applications require different power levels ranging from a few to several hundred horse power. In fact, electrical motors consume around 56% of the total consumed electrical energy, and of this, induction motors account for 96% (M. Shepard, 1992). This shows that around 53% of the total electrical energy is consumed by induction motors. There are general purpose loss minimization techniques approaches of which are different depending on the induction motor drives applications. By using the advances in power electronics and signal processing technologies, the control schemes of induction machines have been improved from simple scalar or auto-tuning control to field oriented and direct torque controls (Abourida, 2009); (Bazzi, 2009); (El Refaei, 2005); (Krause, 1986); (Siva Reddy,

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2000); (Vas, 1990). The field oriented control is successfully applied in real time control of industrial applications when dealing with high performance induction machines drives (Besanelle, 2001); (Holtz, 2006); (Inanc, 2007); (Novotny, 1996); (Singh, 2005); (Wang, 2007). Field oriented control implementation can achieve robust control performance in induction machines. Estimating the magnitude and phase of rotor flux is the key of the control implementation (Abrahamsen, 1997); (Camblong, 2006); (Jemli, 2000). Direct methods in sensing the rotor flux by using suitable hardware around the machine have proved to be inaccurate and impractical at speed and torque variations (Geng, 2004). Indirect methods of sensing the rotor flux employ a mathematical model in induction machine by measuring state variables of currents, voltages and rotor position. The accuracy of this method depends mainly on accuracy of time rotor constant variation (Grouni, 2008); (Marino, 2008); (Wang, 2007). The machine parameters may change during operation which introduces incracies in the estimated flux (Besanelle, 2001). With an aim to improve performance of systems control of induction machine, research has been conducted to design advanced nonlinear controllers (Dhaoui, 2010); (Faiz, 2006); (Holtz, 2006). Most of these controls operate at constant flux norms (Levi, 1995); (Krishan, 2001). In this situation, efficiency is maximized only when the system operates at its nominal torque (Ren, 2008), (Ta, 2001). Away from this operating point the machine will dissipate a considerable part of the injected electrical power as core losses and it may inefficiently store too much energy in its coil inductances (Abrahamsen, 1997); (Thanga Raj, 2009). In most application, induction machines do not operate at the nominal rate since the desired torque may change on-line or may depend on system states such as position or velocity. It is then technically and economically interesting to investigate other modes of flux operation seeking to optimize system performance (Holtz, 2006), (S. Grouni, 2010). Aware of these facts, some previous research works have already used the reference flux as an additional parameter seeking to increase machine efficiency or to maximize the delivered torque in minimum time (Besanelle, 2001); (Camblong, 2006); (Inanc, 2007). The evolution of microprocessor technology and the need for high-performance controllers for drives using induction motors have rise to intensive investigation on advanced control design for AC-drives. The induction motor is known for its versatility and simplicity. It is capable of operating at wide ranges of speeds as well as wide rangers of torques. (S. I. Seleme, 1992).

In this paper, a new optimal control method is suggested to obtain a minimum total energy of induction motors under optimal trajectories of the induction motor's, voltages, torque and speed.

2. Dynamic and energy equations

It is useful to describe the induction motor model by a set of four non-linear differential equations and to choose as state variables the projections of the stator currents and rotor flux (i_{ds} i_{qs} ψ_{dr} ψ_{qr}) on a moving frame into – axis coil (d - q) model on both stator and rotor as described by Krause and Thomas (S. I. Seleme Jr, 1993); (A. Bentounsi, 2002). Fig.1 shows the axial view of an induction machine (L Kirtley, 2003).

The nonlinear differential equations that describe the dynamics of an ideal symmetrical induction motor in a rotating

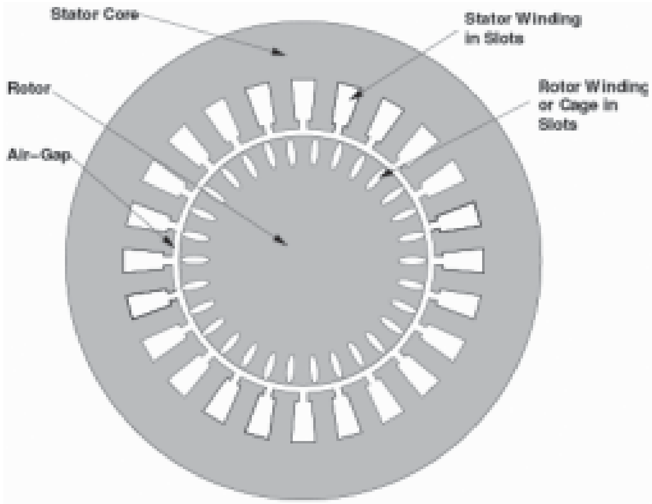

Fig.1 Axial view of an induction machine (L Kirtley. Jr. 2003)

frame is as follows (S. I. Seleme Jr, 1994); (Park, 1991) shows the assignation of these projections for components of the five dimensional state vector.

$$x^T = \begin{bmatrix} i_{ds} & i_{qs} & \psi_{dr} & \psi_{qr} & w_r \end{bmatrix} \quad \text{... (1)}$$

The inputs to the system are the projections of the motor supply voltage (V_s) on the (d–q) axes frame.

$$u^T = \begin{bmatrix} V_{ds} & V_{qs} & T_l \end{bmatrix} \quad \text{... (2)}$$

The output is given by a nonlinear relation between the projections of the flux and currents on the (d–q) axes frame.

$$Te = P\frac{M_{sr}}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \quad \text{... (3)}$$

For large machines, for which the minimum energy criterion is important, the mechanical dynamics of the motor (the mechanical speed w_r) is slow enough compared to the w electrical dynamics of the torque transient so that can be considered as invariant with respect to the state x.

In this paper the author considers the problem of analytically finding optimal voltages references (Fig.2) that minimize total energy.

The model of one pole pair induction motor can be given by:

$$\dot{x} = A.x + Bu \quad \text{... (4)}$$

$$\dot{y} = c.x \quad \text{... (5)}$$

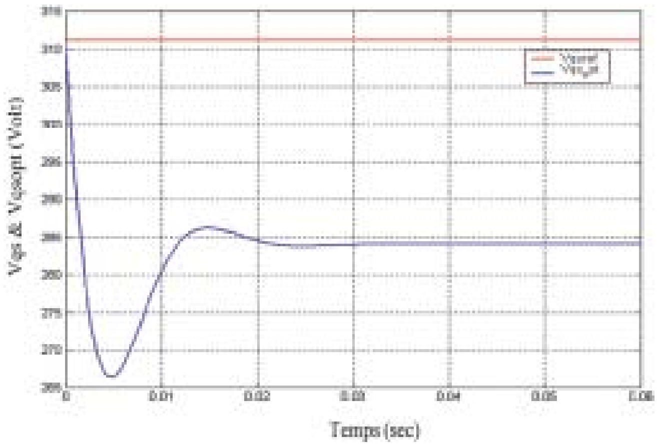

Fig.2. Simulation result of stator voltage input (axe-q) motor with and without optimal controller

3. Modelling hypothesis and model properties

Validity of the model AC-machines are normally, three phase electrical devices which can be reduced to a two phase model due to their symmetry. The classical two phase textbook form of the induction motor model is:

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \\ \dot{\psi}_{dr} \\ \dot{\psi}_{qr} \\ \dot{w}_r \end{bmatrix} = \begin{bmatrix} \left(\frac{\sigma-1}{\sigma\tau_r}-\frac{R_s}{\sigma L_s}\right) & 0 & \frac{M_{sr}}{\sigma\tau_r L_s L_r} & \frac{M_{sr}}{\sigma L_s L_r}w_r & 0 \\ 0 & \left(\frac{\sigma-1}{\sigma\tau_r}-\frac{R_s}{\sigma L_s}\right) & -\left(\frac{M_{sr}}{\sigma L_s L_r}w_r\right) & \frac{M_{sr}}{\sigma\tau_r L_s L_r} & 0 \\ \frac{M_{sr}}{\tau_r} & 0 & -\frac{1}{\tau_r} & -w_r & 0 \\ 0 & \frac{M_{sr}}{\tau_r} & w_r & -\frac{1}{\tau_r} & 0 \\ -\frac{P^2 M_{sr}}{jL_r}\psi_{qr} & \frac{P^2 M_{sr}}{jL_r}\psi_{dr} & 0 & 0 & -\frac{F}{j} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \\ w_r \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{P}{j} \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ T_l \end{bmatrix} \quad \text{... (6)}$$

Where, $(i_{ds}\ i_{qs}\ \psi_{dr}\ \psi_{qr})^T$ are the dq-axis equivalent stator currents, dq-axis equivalent rotor fluxes and mechanical speed, $\lfloor V_{ds}\ \ V_{qs}\ \ T_l \rfloor$ are the dq-axis equivalent stator voltages and the torque load, L_s, L_r and M_{sr} are the stator, rotor and mutual inductance, R_s, R_r are the stator and rotor resistances respectively, $\tau_r = \frac{L_r}{R_r}$ is the rotor time constant, $\sigma = 1 - \frac{M_{sr}^2}{L_s L_r}$ is the leakage coefficient of the machine, F is the viscous friction coefficient of machine and load, J is the inertia constant of the machine, P is the number of pole pairs.

The validity of this model is based on the assumptions already mentioned at the beginning of section five which concern the attribution of constant values for the inductances and resistances of the stator and rotor electric circuit.

There are several methods to solve this non linear optimal control problem such as direct method, discretization method, parameterization method and Taylor expansion about an operating point method (C.J. Goh, 1988); (P.A. Frick, 1995); (J. Vlassenbroeck, 1988); (H. Jaddu, 1999).

To solve this optimal control problem under nonlinear state equation (6), in our paper we using the Taylor expansion $[f(x) = f(\bar{x}) + \frac{df}{dx}(\bar{x})(x-\bar{x})]$, about an operating point $[\bar{x} = (i_{ds0}\quad i_{qs0}\quad \psi_{dr0}\quad \psi_{qr0}\quad w_{r0})]$, to convert the nonlinear optimal control problem into sequence of linear quadratic optimal problems which can be solved by solving sequence of Riccati equations. The optimal trajectories of the induction motor's, voltages, torque and speed are presented in this paper.

Where,

$$\frac{df}{dx}(\bar{x}) = \begin{bmatrix} \frac{df_1}{dx_1}(\bar{x}) & \frac{df_2}{dx_2}(\bar{x}) & . & . & \frac{df_1}{dx_n}(\bar{x}) \\ \frac{df_2}{dx_1}(\bar{x}) & \frac{df_2}{dx_2}(\bar{x}) & . & . & \frac{df_2}{dx_n}(\bar{x}) \\ . & . & . & . & . \\ . & . & . & . & . \\ \frac{df_p}{dx_1}(\bar{x}) & \frac{df_p}{dx_2}(\bar{x}) & . & . & \frac{df_p}{dx_n}(\bar{x}) \end{bmatrix} \quad \text{... (7)}$$

To convert our optimal control problem of induction machine to sequence of linear quadratic optimal control problems we first linearize the state space equation (6) by Taylor expansion about an operating point (7) to get:

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \\ \dot{\psi}_{dr} \\ \dot{\psi}_{qr} \\ \dot{w}_r \end{bmatrix} = \begin{bmatrix} \left(\frac{\sigma-1}{\sigma\tau_r}-\frac{R_s}{\sigma L_s}\right) & 0 & \frac{M_{sr}}{\sigma\tau_r L_s L_r} & \frac{M_{sr}}{\sigma L_s L_r}w_{r0} & 0 \\ 0 & \left(\frac{\sigma-1}{\sigma\tau_r}-\frac{R_s}{\sigma L_s}\right) & -\left(\frac{M_{sr}}{\sigma L_s L_r}w_{r0}\right) & \frac{M_{sr}}{\sigma\tau_r L_s L_r} & 0 \\ \frac{M_{sr}}{\tau_r} & 0 & -\frac{1}{\tau_r} & -w_{r0} & 0 \\ 0 & \frac{M_{sr}}{\tau_r} & w_{r0} & -\frac{1}{\tau_r} & 0 \\ 0 & 0 & 0 & 0 & -\frac{F}{j} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \\ w_r \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{P}{j} \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ T_l \end{bmatrix} \quad \text{... (8)}$$

4. Optimal control design methods

Optimal control is branch of modern control theory that deals with designing controls for dynamic systems by minimizing a performance index that depends on the system variables. (Kh Yousfi, 2005).

In this paper, the author discusses the design of optimal controller for nonlinear systems which quadratic performance index. The object of the optimal regulator design is to determine the optimal control law [U_{opt} (x,t)] which can transfer the system from its initial state to the final state such that a given performance index is minimized. The performance index is selected to give the best trade-off between performance and cost of control. The performance index that widely used in optimal control design is known as the quadratic performance index and is based on minimum error and minimum energy criteria.

Equation (8) represents the linear fifth order model for the induction machine which can be rewritten in a compact form:

$$\dot{x} = A.x + B.u \quad \text{... (9)}$$

The problem is to find the vector [$k(t)$] of the optimal control law:

$$u^*_{opt} = diag\ (k).\ x^* \quad \text{... (10)}$$

This minimizes the value of a quadratic performance index (J) of the form:

$$J = \int (x^T.Q.x + u^T.R.u)dt \xrightarrow{u = u_{opt}} \min \quad \text{... (11)}$$

Subject to the dynamic plant equation (4) in (11),

Where: Q is a positive semi definite matrix and R is a real symmetric matrix, if all principal minors are nonnegative.

The choice of the elements of (Q) and (R) allows the relative weighting of individual state variables and individual control inputs.

To obtain a formal solution, we can use the model of Lagrange multipliers. The constraint problem is solved by augmenting (4) in (11) using the vector of Lagrange multipliers (λ). The problem reduces to the minimization of the following function.

$$\Im(x,u,t) = [x^T.Q.x + u^T.R.u] + \lambda^T.[A.x + B.u - \dot{x}] \quad \text{... (12)}$$

The optimal values are found by equating the partial derivatives to zero:

$$\frac{\partial \Im}{\partial \lambda} = A.x^* + B.u^* - \dot{x}^* = 0 \Rightarrow \dot{x}^* = A.x^* + B.u^* \quad \text{... (13)}$$

$$\frac{\partial \Im}{\partial u} = 2.R.u^* + \lambda^T.B = 0 \Rightarrow u^* = -\frac{1}{2}.R^{-1}.\lambda^T.B \quad \text{... (14)}$$

$$\frac{\partial \Im}{\partial x} = 2.x^*.Q - \dot{\lambda} + \lambda.A^T = 0 \Rightarrow \dot{\lambda} = -2.Q.x^* - A^T.\lambda \quad \text{... (15)}$$

Assume that there exists a symmetric, time-varying positive definite matrix ($p(t)$) satisfying:

$$\lambda = 2.p(t).x^* \quad \text{... (16)}$$

Substituting (16) into (14) gives the optimal closed loop control law:

$$u^* = -R^{-1}.B.p(t).x^* \quad \text{... (17)}$$

Obtaining derivate of (16), we have:

$$\lambda = 2.p(t).x^* \Rightarrow \dot{\lambda} = 2.(\dot{p}(t).x^* + p(t).\dot{x}^*) \quad \text{... (18)}$$

Finally, equating (15) with (18), we obtain:

$$-2.Q.x^* - 2.A^T.p(t).x^* = 2(\dot{p}(t).x^* + p(t).\dot{x}^*) \quad \text{... (19)}$$

$$\dot{p}(t) = -p(t).A - A^T.p(t) - Q + p(t).B.R^{-1}.B^T.p(t) \quad \text{... (20)}$$

The above equation is referred to as the matrix Riccati equation. The boundary condition for (20) is $p(t_f)=0$). Therefore, (21) must be integrated backward in time. Since a numerical solution is performed forward in time, a dummy time variable ($\tau = t_f - t$) is replaced for time (t). Once the solution to (20) is obtained the solution of the state equation (13) in conjunction with the optimum control equation (17):

$$u^*_{opt} = -R^{-1}.B^T.p(t).x^* = diag\ (K).\ x^* \quad \text{... (21)}$$

$$k_i = diag(K) \quad \text{... (22)}$$

The design procedure is in stark contrast to classical control design, where gain matrix (K) is selected directly:

$$\begin{bmatrix} V_{dsopt} \\ V_{qsopt} \\ T_{lopt} \end{bmatrix} = k.\begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \\ w_r \end{bmatrix} \quad \text{... (23)}$$

This has the significant advantages of allowing the entire control loop in a multi-loop system to be closed simultaneously, while guaranteeing closed loop stability. The optimal control law is assuring the minimum energy (Figs.3 and 4), maximum torque (Fig.5) and optimal trajectory of state (IM speed), (Fig.6).

From the following velocity differential equation is obtained:

$$\frac{dw_r}{dt} = \frac{P}{j}(Te - T_{lopt}) - F.w_r \quad \text{... (24)}$$

To look at the reliability of the optimal controller on result them of the active and reactive losses of the plant to consider:

$$P_1 = wr.Te \quad \text{... (25)}$$

$$P_2 = (i_{qs}^2 + i_{ds}^2).R_s + (i_{qr}^2 + i_{dr}^2).R_r \quad \text{... (26)}$$

$$P_3 = \frac{d}{dt}\left(\frac{\sigma L_s}{2}(i_{qs}^2 + i_{ds}^2) + \frac{1}{2L_r}(\psi_{qr}^2 + \psi_{dr}^2)\right) \quad \text{... (27)}$$

The total active and reactive losses in the induction motor are:

$$P_a = P_1 + P_2 + P_3 \quad \text{... (28)}$$

$$Q_r = 2.w_r\left(\frac{\sigma L_s}{2}(i_{qs}^2 + i_{ds}^2) + \frac{1}{2L_r}(\psi_{qr}^2 + \psi_{dr}^2)\right) \quad \text{... (29)}$$

5. Simulation results

In this paper the author has confirmed the validity of the proposed optimal control by Matlab software simulation for an induction machine drive system (Table 1). (Figs.7 to 9) are

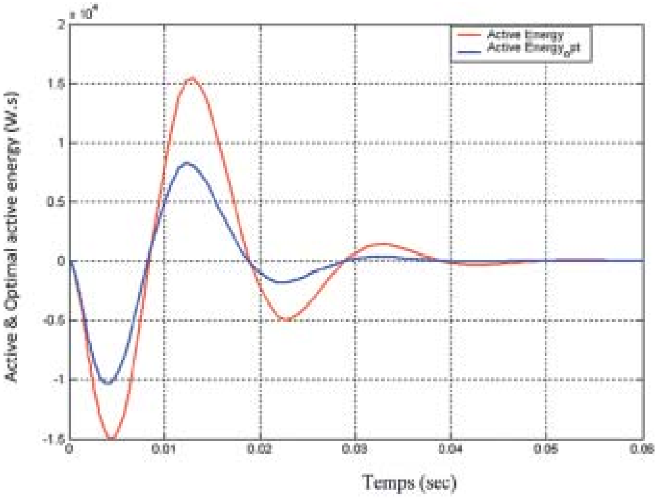

Fig.3. Simulation result of active energy with and without optimal controller

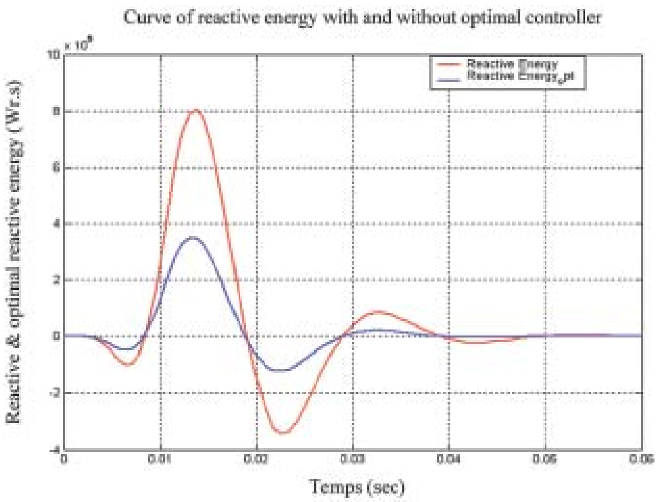

Fig.4. Simulation result of reactive energy with and without optimal controller

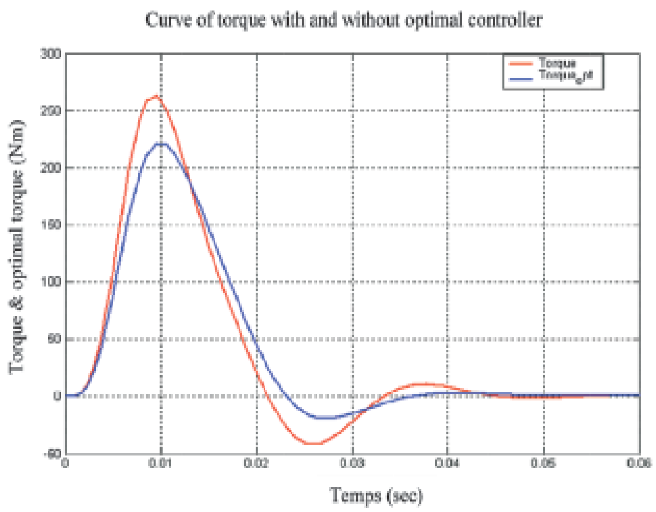

Fig.5 Simulation result of torque with and without optimal controller

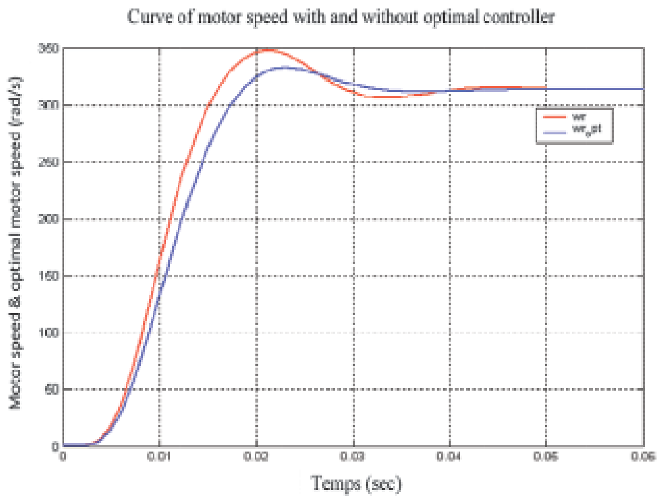

Fig.6 Simulation result of speed with and without optimal controller

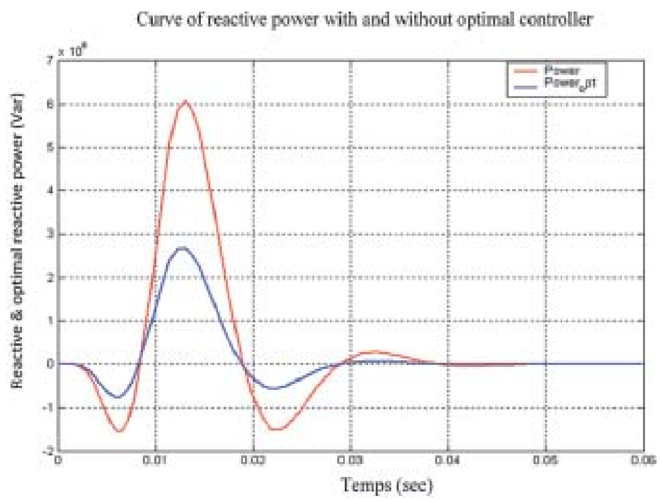

Fig.7 Simulation result of reactive power with and without optimal controller

TABLE 1: INDUCTION MACHINE PARAMETERS

Parameters	Nomenclature	Item (Unit)	Value
Vn	Rated supply voltage	Volt	220/380
fn	Rated supply frequency	Hz	50
P	Number pair of poles	/	2
j	Inertia constant	$Kg.m^2$	0.089
F	Viscous friction constant	Nm/rad/s	0.00187
Rs	Stator resistance	Ω	0.435
Rr	Rotor resistance	Ω	0.816
Ls=Lr	Stator and rotor inductance	H	0.754
Msr	Mutual inductance	H	0.261

shown the simulation models of three phase induction motor with and out optimal controller and optimal controller respectively.

The optimal trajectories of the induction motor's voltages, torque and speed are perfectly realized under optimal energy.

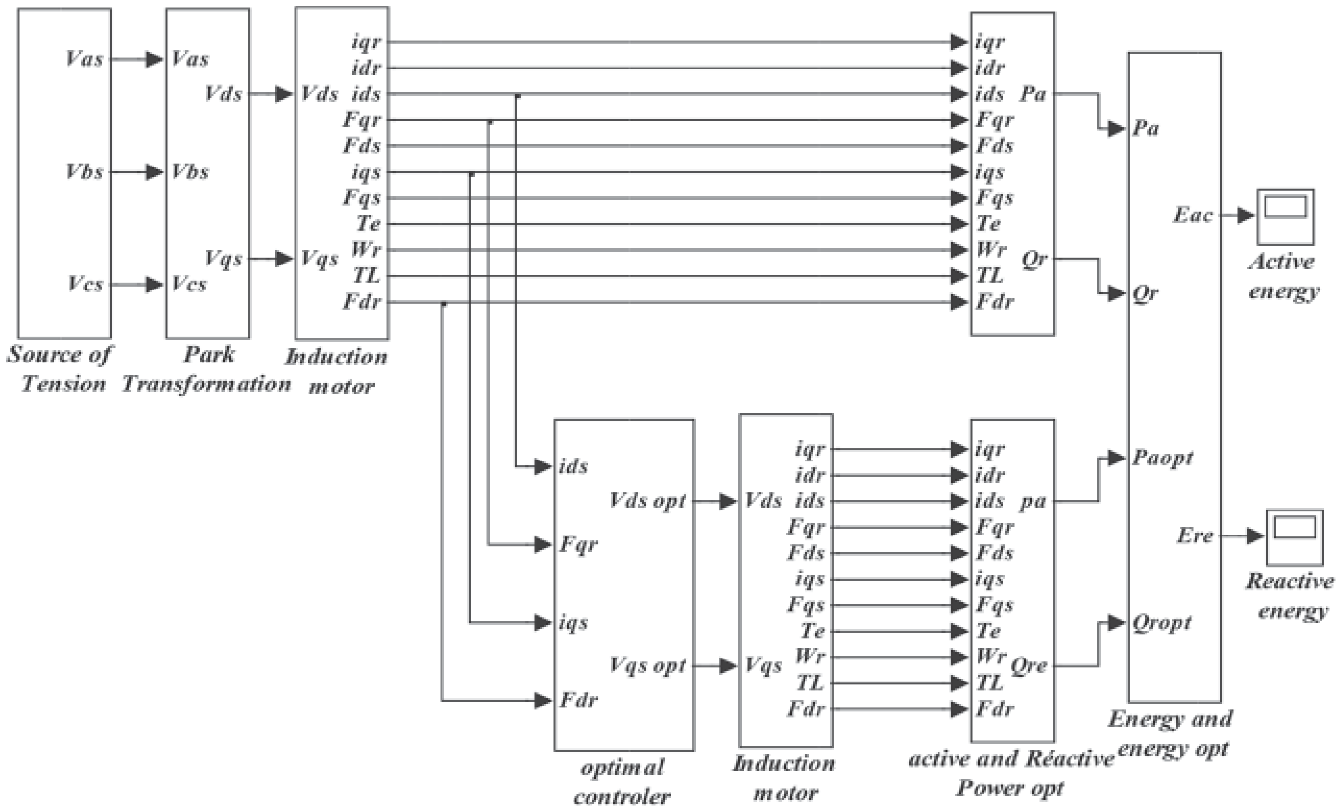

Fig.8. Schema block of three phase Induction Motor with and without optimal controller

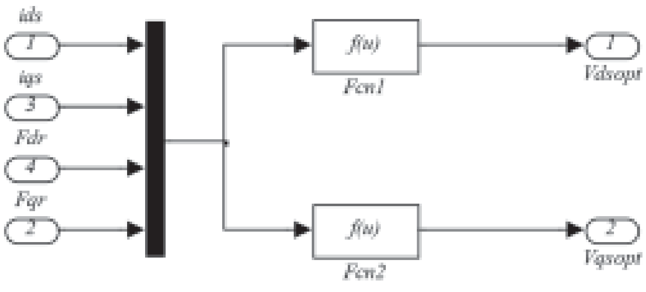

Fig.9 Schema block of optimal Controller

6. Conclusion

In this paper we obtained the optimal trajectory of state (IM speed) and control (IM torque) under optimal energy. These trajectories are obtained by minimizing the quadratic performance measure or total energy (the stored magnetic energy and the coil losses) of the induction motor. Since the induction machine was used to this nonlinear model, the Taylor expansion about an operating point to convert the nonlinear optimal control problem by sequence of linear quadratic optimal problem. The proposed minimum energy approach may be of great interest for application in areas where energy consumption is an import issue; i.e. high speed electric trains and the expected new generation of electrical vehicles. Efficiency optimization is very much essential not only to electrical systems, it require all the systems to get beneficial in terms of money and also reduction in global warning. This paper presented a review of the developments in the field of efficiency optimization of three-phase induction motor through optimal control and design technique. Optimal control covered both the broad approaches namely, loss model control and search control. Optimal design covers the design modifications of materials and construction in order to optimize efficiency of the motor, particularly for the mining machinery such as mining conveyors, crushers and draglines etc.

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