ENERGY-SAVING TECHNOLOGY OF VECTOR CONTROLLED INDUCTION MOTOR BASED ON THE ADAPTIVE NEURO-CONTROLLER

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Abstract. The ongoing evolution of the power system towards a Smart Grid implies an important role of intelligent technologies, but poses strict requirements on their control schemes to preserve stability and controllability. This paper presents the adaptive neuro-controller for the vector control of induction motor within Smart Grid. The validity and effectiveness of the proposed energy-saving technology of vector controlled induction motor based on adaptive neuro-controller are verified by simulation results at different operating conditions over a wide speed range of induction motor.

1. Introduction
In the modern industrial sector induction motors occupy a vital role. As compared to DC drives induction motors play an important role in the safe and efficient operations of industrial plants because of its high efficiency, simplicity of design as well as reliability and relatively low cost and maintenance. There are many different ways to drive an induction motor such as scalar control, vector control, direct torque control and etc. The present paper reviews the main concept of Field Orientated Control (FOC) or vector control of induction motors [1]. In this work we focus on the vector control of induction motor within Smart Grid. The induction motor drive is a dynamic nonlinear system with time varying uncertainties. The ongoing evolution of the nonlinear system of induction motor towards a Smart Grid [2] implies an important role of intelligent technologies, but poses strict requirements on their control schemes to preserve stability and controllability. Nowadays around 70% of electric power is consumed by electric drives. In the industrial sector is increasing the requirements for energy-saving technology. The proportional integral (PI) controllers are widely used in the field-orientated control of induction motor. But it takes even experienced engineers time and effort to regulate the PI coefficients to guarantee good performance. Usually PI controller is tuned only at particular operation point. If the operating point changes then it not operate properly. Therefore, automatic design methods utilizing machine learning techniques such as neuro-controller are a promising alternative as compared to the PI controller. This paper presents the energy-saving technology of vector controlled induction motor based on adaptive neuro-controller within Smart Grid. In this work, the adaptive neuro-controller is designed in two

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steps. The first step objective is dimensionality reduction, which is developed through Principal Component Analysis. The second step objective is to generate control signal, which is developed using selective neural network [3].

2. Mathematical model of the induction motor

The mathematical model of the induction motor used in our work consists of space vector PWM voltage source inverter, induction motor, direct flux and the torque control. Within field-oriented control an induction motor model was established in the $d$-$q$ motor reference frame (without saturation) concept. Figure 1 shows the equivalent circuit which used for obtaining the mathematical model of the induction motor.

![Figure 1. Equivalent circuit of induction motor in $d$-$q$ frame.](image)

The dynamics of the induction motor in $d$-$q$ coordinates established in a rotor flux oriented reference frame is given by the following equations [1]:

\[
V_{ds}^e = R_i j_{ds}^e + p\lambda_{ds}^e - \omega_c \lambda_{qr}^e \\
V_{qs}^e = R_i j_{qs}^e + p\lambda_{qs}^e + \omega_\sigma \lambda_{ds}^e \\
0 = R_i j_{dr}^e + p\lambda_{dr}^e - \omega_c (\omega_c - \omega_r) \lambda_{qr}^e \\
0 = R_i j_{qr}^e + p\lambda_{qr}^e + (\omega_c - \omega_r) \lambda_{dr}^e
\]

where \( \lambda_{ds}^e = L_d i_{ds}^e + L_m i_{dr}^e \), \( \lambda_{qr}^e = L_s i_{qs}^e + L_m i_{qr}^e \), \( \lambda_{dr}^e = L_d i_{dr}^e + L_m i_{ds}^e \), \( \lambda_{qr}^e = L_s i_{qr}^e + L_m i_{qr}^e \).

The electromagnetic torque expressed in terms of inductances is described by equations [2]:

\[
T_e = \frac{3}{2} P L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \\
\frac{d\theta_r}{dt} = \omega_r \\
T_e = j_m \frac{d\omega_r}{dt} + B_m \omega_r + T_I
\]
where $V^e_d$, $V^e_q$ are d-q axis stator voltages respectively; $i^e_d$, $i^e_r$, $i^e_q$, $i^e_{qr}$ are d-q axis stator currents and d-q axis rotor currents respectively; $R_s$, $R_r$ are the stator and rotor resistance per phase respectively; $L_s$, $L_r$, $L_m$ are the self inductances of the stator and rotor and the mutual inductance respectively; $P$ is the number of poles; $p$ is the differentiation operator ($d/dt$); $\omega_e$, $\omega_r$, the speed of the rotating magnetic field and the rotor speed respectively; $T_e$, $T_l$ are the electromagnetic developed torque and the load torque respectively; $J_m$ is the rotor inertia; $B_m$ is the rotor damping coefficient and $\theta_r$ is the rotor position.

3. Field-Orientated Control of induction motor

The field-oriented control (FOC) was initially developed by Blaschke (1971-1973) [4]. Vector control presents following benefits: speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed. In spite of complexity, vector control plays a key role for induction drives, replacing scalar control. The FOC’s key idea is usage projections which transform a three phase time and speed dependent system into a two coordinate time invariant system. This handles instantaneous electrical quantities and makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. Field orientated controlled machines had two constants as input: the torque (aligned with the $q$) and the flux (aligned with $d$). Knowledge of the rotor flux position is the core of the FOC. Field oriented controlled induction machines obtain every DC machine advantage: instantaneous control of the separate quantities allowing accurate transient and steady state management [5]. Figure 2 shows the core principle of indirect vector control.

![Figure 2. Phasor diagram of indirect vector controlled induction machine.](image)

The axes are fixed on the stator, but the $d'$-$q'$ axes, which are fixed on the rotor, are $d'$-$q'$ moving at speed $\omega_r$. Synchronously rotating axes $d'$-$q'$ are rotating ahead of the $d'$-$q'$ axes by the positive slip angle $\theta_{sl}$ corresponding to slip frequency $\omega_{sl}$. The induction motor always relies on a small difference in speed between the stator rotating magnetic field and the rotor shaft speed called slip to induce rotor current in the rotor AC winding [2]. If the speed controller is intelligently designed, it will have the ability to minimize de-tuning effects and the drive performance will be very robust [3].

3. The adaptive neuro-controller for vector controlled induction motor drive

In order to improve effectiveness of indirect vector controlled induction machine we designed the adaptive neuro-controller. We created the adaptive neuro-controller using input-output
data

\[(X, i_q)\]  \hspace{1cm} (1)

generated from the Simulink model of vector controlled induction machine (Fig. 3) [7].

\[x \in \mathbb{R}^{21}\]

\[x \in \mathbb{R}^{5}\]

\[x = (i_{sa}, i_{sb}, i_{sc}, \text{electromagnetic moment}, \text{speed of rotor})\]

The proposed scheme with adaptive neuro-controller was implemented using MATLAB/Simulink software.

\[\text{Figure 3. Simulink model of indirect vector controlled induction machine. [7]}\]

In this work, the adaptive neuro-controller is designed in two steps. The first step objective is dimensionality reduction of data (1) \((X \in \mathbb{R}^{21})\) from 21 to 5, which is developed through Principal Component Analysis. This step forms training data set \((x, i_q)\) for the selective neural network \((x \subseteq X, x \in \mathbb{R}^5)\). The statistical features \(x = (i_{sa}, i_{sb}, i_{sc}, \text{electromagnetic moment}, \text{speed of rotor})\) extracted from the data (1) are used as inputs to selective neural network. The second step objective is to generate control signal \(i_q\), which is developed using the selective neural network [3]. The selective neural networks have capable of machine learning as well as pattern recognition thanks to their adaptive nature. The fulfilling of the structure and learning algorithm of the selective neural network are explained as follows [3].
controller.

In order to verify the performance and effectiveness of proposed control scheme with adaptive neuro-controller comparative simulations was conducted in MATLAB/Simulink. (Fig.4)

4. Simulation results

Simulation was conducted among Matlab/Simulink package. In this paper, the pattern of the reference model $i_q$ that was used to train of the proposed controller for the vector controlled induction motor and the adaptive neuro-controller’s control signals are shown in Fig 5. The parameters for the induction motor are $460\text{V}$, $60\text{Hz}$, $\text{Poles}=4$, $R_s=14.85\times 10^{-3}\Omega$, $R_r=9.295\times 10^{-3}\Omega$, $L_s=0.3027\times 10^{-3}\text{H}$, $L_r=0.3027\times 10^{-3}\text{H}$, $L_m=10.46\times 10^{-3}\text{H}$, $J=3.1\text{kg-m}^2$.

![Fig 5. The pattern of the reference model $i_q$ (training data) and the adaptive neuro-controller's output.](image)

In our work we compared PI and the adaptive neuro-controller for speed control of vector control induction motor drive. Figure 6 shows that the proposed scheme with adaptive neuro-controller provides energy saving due reduction of losses in the windings of the stator current as compared with PI controller.

![Adaptive neuro-controller vs PI controller](image)
The aforementioned dynamic simulation results performance and robustness of the proposed energy-saving technology of induction motor based on adaptive neuro-controller are confirmed as compared to PI controller. Also the energy-saving technology of vector controlled induction motor based on adaptive neuro-controller demonstrates the good quality and robustness in the system dynamic response and reduction in the steady-state and transient motor ripple torque.

5. Conclusions

The validity and effectiveness of the proposed energy-saving technology of vector controlled induction motor based on adaptive neuro-controller are verified by simulation results at different operating conditions over a wide speed range of induction motor.

Based on simulation comparative results, the following conclusions are made:

- the proposed scheme with adaptive neuro-controller has better performance over PI controller;
- the proposed adaptive neuro-controller provides energy saving due reduction of losses in the windings of the stator current as compared with PI controller;
- the proposed energy-saving technology of vector controlled induction motor based on adaptive neuro-controller is more robust during the load changes and eliminates the transients during sudden changes in speed;
- the performance of the adaptive neuro-controller is improved by reducing the ripple torque as compared with PI controller;
- the simulation results under random perturbation identified the obvious validity of the proposed energy-saving technology of vector controlled induction motor based on adaptive neuro-controller.

Thus it is found that the energy-saving technology of vector controlled induction motor based on adaptive neuro-controller can be effectively used to control induction motor drive in practice.

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