A Fuzzy Adaptive Nonlinear Control for an Asynchronous Machine

Moulay Fatima

Faculty of technology, IRECOM
Laboratory
University of Djillali Liabes,
Sidi Bel Abbes, Algeria.
fatimamoulay66@yahoo.fr

Habbatti Assia

Faculty of technology, IRECOM
Laboratory,
University of Djillali Liabes,
Sidi Bel Abbes, Algeria.
bellia_abdeljalil@yahoo.fr

Hamdaoui Habib

Faculty of technology, IRECOM
Laboratory,
University of Djillali Liabes,
Sidi Bel Abbes, Algeria.
hamdaoui_h@outlook.fr

Abstract: This paper presents the general concept of the nonlinear control of the asynchronous machine. The decoupling between the flux and the speed is realized by the input-output linearization technique. In this work, a nonlinear adaptive control method has been applied to the asynchronous machine and we give some initial results on the adaptive fuzzy logic control of nonlinear systems, linearized by state feedback. The adaptations of the parameters are used as a technique for robustifying the exact cancellation of the nonlinear terms, which is called for the linearization technique. The performance of the proposed nonlinear adaptive control scheme is demonstrated by simulation results. These results show that the proposed method achieves the desired dynamic performance.

Keywords: Asynchronous machine, nonlinear control and adaptive fuzzy logic control

I. INTRODUCTION

Most variable drives use the asynchronous machine because of its many advantages in performance and robustness. Its main disadvantage lies in the complexity of its multivariable model which is non-linear and strongly decoupled [1]. The vector control technique, which is based on flux orientation, allows flux and torque to be independently decoupled and controlled. However, exact knowledge of the flux position poses a problem of precision [2]. The input-output linearization technique, with a non-linear state feedback control, allows the machine model to be broken down into two linear, monovariable and independent sub-systems. Thus, conventional or modern control techniques can be easily applied. The tracking of the reference trajectories is based on the principle of the optimal imposition of the poles. This technique has the advantage of controlling the torque itself in regulation. Conventional control algorithms appear to be inadequate if the controlled part is subject to disturbances and parametric variations. Thus, some authors propose adaptive control by reference model [3], others robust controllers [4]. In this work, an adaptive non-linear control is realized which regulates the flux and the speed of the asynchronous machine and maintains the decoupling between them. In this part, only parameters that fit in a linear way into the machine model will be taken into account. It is the rotor resistance R_r and the resistant torque C_r . To do so, we first design a command based on the linearization technique in the input-output sense applied to the nominal model, then we calculate the adaptation law that will estimate the vector uncertain parameters [5].

In the case of the asynchronous machine, the uncertain parameters are mainly the stator and rotor resistances (which depend on the temperature), the inductances (which depend on the saturation level), the moment of inertia as well as the load torque (which are difficult to quantify). Moreover, by examining the model, we can notice that two of these parameters return in a linear way in the model (resistances and load torque) while the two others return in a non-linear way (inductances and moment of inertia).

At the same time, a large amount of research has been devoted to the development of nonlinear adaptive methodologies combining the linearization technique with adaptive methods. All methods have yielded satisfactory results, but they limit model structures and how they depend on uncertain parameters. Indeed, most of the methods proposed in the literature are intended for the case where the uncertain parameters fit in a linear fashion in the model.

II. MODEL OF THE ASYNCHRONOUS MACHINE

A. Putting in nonlinear state equations

The dynamic equations of the asynchronous machine in α , β repository are:

$$\frac{d}{dt} \begin{bmatrix} \Omega_m \\ \psi_a \\ \psi_b \\ i_a \\ i_b \end{bmatrix} = \begin{bmatrix} \mu(\psi_a i_a - \psi_b i_b) - \frac{C_r}{J} \\ -\alpha \psi_a - n_p \Omega_m \psi_b + \alpha M i_a \\ n_p \Omega_m \psi_a - \alpha \psi_b + \alpha M i_b \\ \alpha \beta \psi_a + n_p \beta \Omega_m \psi_b - \gamma i_a \\ -n_p \beta \Omega_m \psi_a + \alpha \beta \psi_b - \gamma i_b \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \end{bmatrix} \quad (1)$$

The system of equations is rewritten in the form suggested for the application of linearization in the input-output sense as follows:

$$\dot{x} = f(x) + g(x)u \quad (2)$$

Where the vector of states x and commands u are:

$$x = [x_1, x_2, x_3, x_4, x_5]^T = [\Omega_m, \psi_a, \psi_b, i_a, i_b]^T$$

And:

$$u = [u_a \ u_b]^T$$

Witch: $\Omega_m, \psi_a, \psi_b, i_a, i_b$ are simultaneously, the rotor speed, the components a,b of the rotor flux and the components a ,b of the current

with :

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \\ f_5(x) \end{bmatrix} = \begin{bmatrix} \mu(\psi_a i_a - \psi_b i_b) - \frac{Cr}{J} \\ -\alpha\psi_a - n_p \Omega_m \psi_b + \alpha M i_a \\ n_p \Omega_m \psi_a - \alpha\psi_b + \alpha M i_b \\ \alpha\beta\psi_a + n_p \beta \Omega_m \psi_b - \gamma i_a \\ -n_p \beta \Omega_m \psi_a + \alpha\beta\psi_b - \gamma i_b \end{bmatrix} \quad (3)$$

And

$$g(x) = \begin{bmatrix} g_a(x) \\ g_b(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{\sigma L_s} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sigma L_s} \end{bmatrix}^T \quad (4)$$

B. Regulated Outputs and Ordering Criteria

It is desired to control the speed and the norm of the voltage imposes to lower the norm of the flux so one must also control the norm of the rotor flux. In this panel, the outputs must be the rotor speed and the standard (modulus) of the rotor flux [6].

The outputs chosen to be controlled are thus:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} \Omega_m \\ \psi_r^2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2^2 + x_3^2 \end{bmatrix} \quad (5)$$

III. ADAPTIVE FUZZY CONTROLLER DESIGN STEPS

The approach developed in this paper is based on the guarantee of the robustness of the control structures towards the uncertainties and / or disturbances affecting the system. This robustness can be seen as a total compensation or mitigation of the influence of uncertainties and / or disturbances on the tracking and control performance [7, 8].

The design is done in two steps: In the first, the design of the non-adaptive controller is carried out using the nominal model. In the second, however, we propose to estimate the uncertain nonlinear functions by fuzzy systems and from the good choice of the law of adaptation

Consider the multivariable dynamic system:

$$\dot{x} = f(x, p) + \sum_{i=1}^m g_i(x, p) u_i \quad (6)$$

With:

$$\begin{aligned} f(x, p) &= f_n(x) + \Delta f(x, p) \\ g_i(x, p) &= g_{ni}(x) + \Delta g_i(x, p) \end{aligned} \quad (7)$$

$f(x)$, $g_i(x)$, represent the nominal model ($p=0$), that is to say

:

$$\dot{x} = f_n(x) + \sum_{i=1}^m g_{ni}(x) u_i \quad (8)$$

While $\Delta f(x, p)$, $\Delta g_i(x, p)$ represent the part produced by the uncertain parameters.

Then, one can rewrite the equations of the machine in the form suggested by (6):

$$\begin{aligned} \dot{x} &= [f_n(x) + \Delta f(x)] + \\ &[g_{an}(x) + \Delta g_a(x)] u_a + \\ &[g_{bn}(x) + \Delta g_b(x)] u_b \end{aligned} \quad (9)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix}$$

Where:

f_n, g_{an} and g_{bn} Represent the known non-linear functions they are given by equations (3) and (4).

$\Delta f, \Delta g_a$ and Δg_b Are unknown nonlinear functions.

They model the uncertain part of the model in which one will take into account any variation on the parameters.

As the objective of the work is to solve the trajectory tracking problem, the fuzzy control law will be obtained from a fuzzy model representing the unknown non-linear functions. The solution envisaged consists in increasing the control law of the nominal model by a fuzzy additive command. In this case, the control structure can ensure robustness with respect to parametric variations [9, 10].

A. Change of coordinates:

Let's define the new coordinate change y:

$$\begin{aligned} y_1 &= h_1(x) \\ y_2 &= L_{f_n} h_1(x) + L_{\Delta f} h_1(x) \\ y_3 &= h_2(x) \\ y_4 &= L_{f_n} h_2(x) + L_{\Delta f} h_2(x) \end{aligned} \quad (10)$$

Let us write the system (9) in the coordinates y defined by (10):

$$\begin{aligned} \dot{y}_1 &= y_2 = L_{f_n} h_1(x) + L_{\Delta f} h_1(x) \\ \dot{y}_2 &= [L_{f_n}^2 h_1(x) + L_{\Delta f}^2 h_1(x)] + \\ &\left[L_{g_{an}} L_{f_n} h_1(x) + L_{g_{an}} L_{\Delta f} h_1(x) + \right. \\ &\left. L_{\Delta g_a} L_{f_n} h_1(x) + L_{\Delta g_a} L_{\Delta f} h_1(x) \right] u_a \\ &+ \left[L_{g_{bn}} L_{f_n} h_1(x) + L_{g_{bn}} L_{\Delta f} h_1(x) \right. \\ &\left. + L_{\Delta g_b} L_{f_n} h_1(x) + L_{\Delta g_b} L_{\Delta f} h_1(x) \right] u_b \\ \dot{y}_3 &= y_4 = L_{f_n} h_2(x) + L_{\Delta f} h_2(x) \\ \dot{y}_4 &= [L_{f_n}^2 h_2(x) + L_{\Delta f}^2 h_2(x)] + \\ &\left[L_{g_{an}} L_{f_n} h_2(x) + L_{g_{an}} L_{\Delta f} h_2(x) + \right. \\ &\left. L_{\Delta g_a} L_{f_n} h_2(x) + L_{\Delta g_a} L_{\Delta f} h_2(x) \right] u_a \\ &+ \left[L_{g_{bn}} L_{f_n} h_2(x) + L_{g_{bn}} L_{\Delta f} h_2(x) + \right. \\ &\left. L_{\Delta g_b} L_{f_n} h_2(x) + L_{\Delta g_b} L_{\Delta f} h_2(x) \right] u_b \end{aligned} \quad (11)$$

B. Fuzzy approximators of unknown nonlinear functions

In this part, Takagi-Sugeno's fuzzy systems will be adopted to represent the dynamics of unknown non-linear functions [11, 12].

We can write:

$$\begin{aligned}\alpha_i &= W_{\alpha_i}^T \theta_{\alpha_i}^* \\ \beta_i &= W_{\beta_i}^T \theta_{\beta_i}^* \\ \gamma_{ij} &= W_{\gamma_{ij}}^T \theta_{\gamma_{ij}}^*\end{aligned}\quad (12)$$

Where $\theta_{\alpha_i}^*$, $\theta_{\beta_i}^*$ and $\theta_{\gamma_{ij}}^*$ are the vectors of optimal parameters when the unknown part of the model of the asynchronous machine is represented by the fuzzy systems.

Assume that fuzzy estimates of unknown nonlinear functions containing parameter deviations are given by:

$$\begin{aligned}\hat{\alpha}_i &= W_{\alpha_i}^T \theta_{\alpha_i} \\ \hat{\beta}_i &= W_{\beta_i}^T \theta_{\beta_i} \\ \hat{\gamma}_{ij} &= W_{\gamma_{ij}}^T \theta_{\gamma_{ij}}\end{aligned}\quad (13)$$

The matrices of errors on these parameters are:

$$\begin{aligned}e_{\theta_{\alpha_i}} &= \theta_{\alpha_i}^* - \theta_{\alpha_i} \\ e_{\theta_{\beta_i}} &= \theta_{\beta_i}^* - \theta_{\beta_i} \\ e_{\theta_{\gamma_{ij}}} &= \theta_{\gamma_{ij}}^* - \theta_{\gamma_{ij}}\end{aligned}\quad (14)$$

Now we introduce the estimated parameters $\hat{\alpha}_i$, $\hat{\beta}_i$ and $\hat{\gamma}_{ij}$, $i, j = 1 \div 2$, in the new coordinates defined by:

$$\begin{cases} z_1 = y_1 \\ z_2 = y_2 + \hat{\alpha}_1(x) \\ z_3 = y_3 \\ z_4 = y_4 + \hat{\alpha}_2(x) \end{cases}\quad (15)$$

$$\begin{aligned}\dot{z}_1 &= z_2 \\ \dot{z}_2 &= \left[L_{f_n}^2 h_1(x) + \hat{\beta}_1(x) \right] \\ &+ \left[L_{g_{an}} L_{f_n} h_1(x) + \hat{\gamma}_{11}(x) \right] u_a \\ &+ \left[L_{g_{bn}} L_{f_n} h_1(x) + \hat{\gamma}_{12}(x) \right] u_b \\ \dot{z}_3 &= z_4 \\ \dot{z}_4 &= \left[L_{f_n}^2 h_2(x) + \hat{\beta}_2(x) \right] \\ &+ \left[L_{g_{an}} L_{f_n} h_2(x) + \hat{\gamma}_{21}(x) \right] u_a \\ &+ \left[L_{g_{bn}} L_{f_n} h_2(x) + \hat{\gamma}_{22}(x) \right] u_b\end{aligned}\quad (16)$$

The system (11) becomes:

The following fuzzy command law:

$$\begin{bmatrix} u_a \\ u_b \end{bmatrix} = D^{-1}(x, \hat{\gamma}) \left[\begin{pmatrix} -\xi_1(x, \hat{\beta}_1) \\ -\xi_2(x, \hat{\beta}_2) \end{pmatrix} + \begin{pmatrix} v_a \\ v_b \end{pmatrix} \right]\quad (17)$$

Where:

$$\begin{aligned}\xi_1(x, \hat{\beta}_1) &= L_{f_n}^2 h_1(x) + \hat{\beta}_1(x) \quad \text{and} \\ \xi_2(x, \hat{\beta}_2) &= L_{f_n}^2 h_2(x) + \hat{\beta}_2(x)\end{aligned}$$

And

$$D(x, \hat{\gamma}) = \begin{bmatrix} L_{g_{an}} L_{f_n} h_1(x) + \hat{\gamma}_{11}(x) & L_{g_{bn}} L_{f_n} h_1(x) + \hat{\gamma}_{12}(x) \\ L_{g_{an}} L_{f_n} h_2(x) + \hat{\gamma}_{21}(x) & L_{g_{bn}} L_{f_n} h_2(x) + \hat{\gamma}_{22}(x) \end{bmatrix}$$

Makes the system (16) completely linearized and decoupled, that is to say:

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = v_a \\ \dot{z}_3 = z_4 \\ \dot{z}_4 = v_b \end{cases} \Leftrightarrow \begin{bmatrix} \ddot{y}_1 \\ \ddot{y}_3 \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \end{bmatrix}\quad (18)$$

The new stabilizing controls and are given by:

$$\begin{cases} v_a = -k_{a1} z_1 - k_{a2} z_2 + v_{a \text{ ref}} \\ v_b = -k_{b1} z_3 - k_{b2} z_4 + v_{b \text{ ref}} \end{cases}\quad (19)$$

Where:

$$\begin{cases} v_{a \text{ ref}} = k_{a1} \Omega_{m \text{ ref}}(t) + k_{a2} \dot{\Omega}_{m \text{ ref}}(t) + \ddot{\Omega}_{m \text{ ref}}(t) \\ v_{b \text{ ref}} = k_{b1} |\psi_{\text{ref}}|^2(t) + k_{b2} |\dot{\psi}_{\text{ref}}|^2(t) + |\ddot{\psi}_{\text{ref}}|^2(t) \end{cases}\quad (20)$$

Control parameters $(k_{a1}, k_{a2}), (k_{b1}, k_{b2})$ are chosen so that:

$$K_a = \begin{bmatrix} 0 & 1 \\ -k_{a1} & -k_{a2} \end{bmatrix}, \quad K_b = \begin{bmatrix} 0 & 1 \\ -k_{b1} & -k_{b2} \end{bmatrix}\quad (21)$$

Are asymptotically stable.

If the coefficients (k_{a1}, k_{a2}) and (k_{b1}, k_{b2}) are chosen so as to satisfy the two Hurwitz polynomials

$$\begin{aligned}k_{a1} + k_{a2} p + p^2 &= 0 \\ k_{b1} + k_{b2} p + p^2 &= 0\end{aligned}\quad (22)$$

Have stable poles, then tracking errors converge to zero, when $t \rightarrow \infty$, which ensures the stability of the control structure [13, 14].

C. Reference Model

Now define the reference model as follows:

$$\begin{aligned}\begin{pmatrix} \dot{z}_{1m} \\ \dot{z}_{2m} \end{pmatrix} &= K_a \begin{pmatrix} z_{1m} \\ z_{2m} \end{pmatrix} + \begin{pmatrix} 0 \\ v_{a \text{ ref}} \end{pmatrix} \\ \begin{pmatrix} \dot{z}_{3m} \\ \dot{z}_{4m} \end{pmatrix} &= K_b \begin{pmatrix} z_{3m} \\ z_{4m} \end{pmatrix} + \begin{pmatrix} 0 \\ v_{b \text{ ref}} \end{pmatrix}\end{aligned}\quad (23)$$

Then the tracking error is given by:

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} z_1 - z_{1m} \\ z_2 - z_{2m} \\ z_3 - z_{3m} \\ z_4 - z_{4m} \end{bmatrix} \quad (24)$$

The dynamics of these errors are calculated as follows:

$$\begin{aligned} \dot{e}_1 &= \dot{z}_1 - \dot{z}_{1m} = \dot{y}_1 - \dot{z}_{1m} = \\ &= y_2 + \alpha_1(x) - z_{2m} \\ &= y_2 + \alpha_1(x) + e_2 - z_2 = \\ &= y_2 + \alpha_1(x) + e_2 - [(y_2 + \hat{\alpha}_1(x))] \\ &= e_2 + \alpha_1(x) - \hat{\alpha}_1(x) \end{aligned} \quad (25)$$

from where :

$$\begin{aligned} \dot{e}_1 &= e_2 + W_{\alpha_1}^T e_{\theta_{\alpha_1}} \quad (26) \\ \dot{e}_2 &= [\beta_1(x) - \hat{\beta}_1(x)] \\ &+ [\gamma_{11}(x) - \hat{\gamma}_{11}(x)] u_a \\ &+ [\gamma_{12}(x) - \hat{\gamma}_{12}(x)] u_b \\ &- K_{a1}(z_1 - z_{1m}) - K_{a2}(z_2 - z_{2m}) \end{aligned} \quad (27)$$

For the second error, we have:

$$\begin{aligned} \dot{e}_2 &= \dot{z}_2 - \dot{z}_{2m} \\ &= [L_{f_n}^2 h_1(x) + \beta_1(x)] \\ &+ [L_{g_{an}} L_{f_n} h_1(x) + \gamma_{11}(x)] u_a \\ &+ [L_{g_{bn}} L_{f_n} h_1(x) + \gamma_{12}(x)] u_b \\ &+ K_{a1} z_{1m} + K_{a2} z_{2m} - K_{a1} z_1 - K_{a2} z_2 - v_a \end{aligned} \quad (28)$$

In the same way, we obtain for the second exit:

$$\dot{e}_3 = e_4 + W_{\alpha_2}^T e_{\theta_{\alpha_2}} \quad (29)$$

And

$$\begin{aligned} \dot{e}_4 &= -K_{b1} e_3 - K_{b2} e_4 \\ &+ W_{\beta_2}^T e_{\theta_{\beta_2}} + W_{\gamma_{21}}^T e_{\theta_{\gamma_{21}}} u_a \\ &+ W_{\gamma_{22}}^T e_{\theta_{\gamma_{22}}} u_b \end{aligned} \quad (30)$$

In the condensed matrix form:

$$\dot{e} = Ke + W e_{\theta} \quad (31)$$

W is the regression matrix.

P is a positive definite symmetric matrix and that is the solution of the Lyapunov equation:

$$K^T P + PK = -Q \quad (32)$$

D. Adaptation Law

Consider the quadratic function of Lyapunov:

$$V = e^T P e + e_{\theta}^T \Gamma e_{\theta} \quad (33)$$

Γ is a positive definite symmetric matrix.

The derivative of the Lyapunov V function is::

$$\begin{aligned} \frac{dV}{dt} &= e^T (K^T P + PK) e \\ &+ 2e_{\theta}^T \left(W^T P e + \Gamma \frac{de_{\theta}}{dt} \right) \end{aligned} \quad (34)$$

We now define the adaptation law as follows:

$$\frac{de_{\theta}}{dt} = -\Gamma^{-1} W^T P e \quad (35)$$

Or

$$\frac{d\hat{\theta}}{dt} = \Gamma^{-1} W^T P e \quad (36)$$

This adaptation law defines the dynamics of the parameters of the fuzzy systems to estimate $\hat{\theta}(t)$.

Replacing the adaptation law (34) in (33) using (31), we find[15]:

$$\frac{dV}{dt} = -e^T Q e \leq 0 \quad (37)$$

Inequality $\dot{V} \leq 0$ ensures that $e(t)$ and e_{θ} are bounded which proves the stability of the adaptive control structure. In addition, according to Barbalat's lemma, the tracking error $e(t)$ and those on the estimated parameters $e_{\theta}(t)$ tend towards 0 when $t \rightarrow \infty$.

IV. SIMULATION OF ADAPTIVE FUZZY I / O LINEARIZATION CONTROL

We test the performance of the proposed adaptive controller with Matlab software.

The parameters of the asynchronous machine are, taken from [7] :

$$P=1.5\text{kW}, p=2$$

$$U=380/220\text{V}, 50\text{Hz}, N=1450\text{tr/min}$$

$$I=3/6\text{A}, M=0.258\text{H}$$

$$R_s=4.85\text{ohm}, R_r=3.81\text{ohm}$$

$$L_s=0.274\text{H}, L_r=0.274\text{H}$$

$$J=0.031\text{Kg.m}^2.$$

The performances of the L.I.O.F.A for the control of the asynchronous machine are evaluated after the numerical simulation study.

We found it interesting to compare the performance of the L.I.O.F.A command with the L.I.O.A

To better show the robustness of the L.I.O.F.A compared to L.I.O.A, we have varied the stator inductance and the rotor resistance at $t = 1.5$ s.

 Figure 1. Nonlinear functions L_{ph1} and L_{ph2} when R_r increases by 50%.

 Figure 2. Non-linear functions L^2_{ph1} and L^2_{ph2} when R_r increases by 50%

 Figure 3. Speed and rotor flux when R_r increases by 50%.

 Figure 4. Speed and rotor flow when LS increases by 5%.

 Figure 5. Nonlinear functions L_{ph1} and L_{ph2} when LS increases by 50%.

 Figure 6. Nonlinear functions L^2_{ph1} and L^2_{ph2} when LS increases by 50%.

 Figure 7. Speed and rotor flow when LS increases by 50%.

V. CONCLUSION

In this work, we have proposed a fuzzy, adaptive and stable input-output linearization technique for controlling the asynchronous machine. This technique makes it possible to solve the convergence problem by exploiting both the tracking error and the modeling error. It also ensures the stabilization of the parameters of the fuzzy model while guaranteeing satisfactory tracking performance and has the advantage of always being applicable.

We have proved the stability of this control method and we have shown that it guarantees asymptotic convergence to zero tracking errors. The synthesis of the adaptation law is based on the resolution of the Lyapunov equation.

Thus, the simulation results show the advantages of the control technique proposed in this paper, compared to others.

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