A DUAL-MODE ADAPTIVE ROBUST CONTROLLER APPLIED TO THE SPEED CONTROL OF A THREE-PHASE INDUCTION MOTOR

Caio D. Cunha, Aldayr D. Araujo, David S. Barbalho, and Francisco C. Mota

ABSTRACT

This work presents a Dual-Mode Adaptive Robust Controller applied to the angular shaft speed control of a three-phase induction motor. A liaison between a Model Reference Adaptive Controller (MRAC) and a Variable Structure Model Reference Adaptive Controller (VS-MRAC) through a tuning parameter is obtained using fuzzy logic. The basic idea of the Dual-Mode controller is adding both the advantages of the VS-MRAC transient behavior with the steady-state properties of the conventional MRAC.

KeyWords: Variable structure systems, adaptive control.

I. INTRODUCTION

In recent days the induction motors have been increasingly replacing the DC motors in high performance electrical motor drivers [1]. In the technique of vectorial control based on the rotor field orientation [1-2], an important element of uncertainty is the value of the rotor time constant that varies with the operation conditions, changing the system behavior.

In the conventional Model Reference Adaptive Control (MRAC) with integral adaptation laws, even with the modifications to increase the robustness of the conventional algorithm (σ factor, normalization, etc.) [3], in general, the transient is slow and oscillatory. Hsu and Costa [4] proposed a variable structure model reference adaptive controller (VS-MRAC), using the control structure of MRAC and switching control laws as in Variable Structure Systems (VSC) [5]. In spite of the good transient response, in general we have a control signal with the occurrence of chattering phenomenon. The dual-mode controller, suggested by Hsu and Costa [6] and Hsu et al. [7] is based on the work of Emelyanov [8] and proposes a connection between VS-MRAC and conventional MRAC. The idea is to have an algorithm between the conventional MRAC and VS-MRAC in which the chattering problem can be minimized while the good transient properties are preserved.

In this work we propose that the transition between the MRAC and VS-MRAC can be made on line, using the VS-MRAC during the transient and converging to MRAC when the system approaches the steady state. The goal is to have a robust system with fast response and small oscillations (characteristics of the VS-MRAC) and a smooth steady state control signal (characteristics of the MRAC). The transition between the VS-MRAC and MRAC is done by tuning just one parameter (μ) in the control law [9] by using a fuzzy logic rule [10]. When this parameter approaches zero the algorithm converges to VS-MRAC, when it approaches one the algorithm converges to MRAC, the intermediate values representing the transition between one and another controller.

II. MODEL OF THE INDUCTION MOTOR

Using the vectorial analysis with the rotor flux orientation [1-2], we obtain the following expression for the torque

$$T_e(t) = K_r \psi_{st}(t) i_{dq}(t)$$  \hspace{1cm} (1)
where $K_e$ is a positive constant.

The Eq. (1) describes the induction motor torque in a similar way to the DC machine. The component of the rotor flux vector on the direct axis ($\psi_{rd}$) is equivalent to the field flux in a DC machine and the component of stator electrical current vector on the quadrature axis ($i_{sq}$) is equivalent to the armature current in a DC machine. Additionally, if the component of the rotor flux is kept constant, the torque can be controlled only by the component of the stator electrical current vector on the quadrature axis.

**III. CONTROLLER STRUCTURE**

### 3.1 MRAC controller

The dynamic of the induction motor is represented by the following equation

$$ J \frac{d\omega(t)}{dt} = T_e(t) - B\omega(t) - T_l(t) $$

where $J$ is the moment of inertia of the rotational mass, $B$ is the damping constant, $T_e$ is the induction motor torque, $\omega$ is the rotor angular mechanical speed and $T_l$ is the load torque.

The induction motor model introduced here (Eqs. (1) and (2)), for a certain operating point, yields to a first order model given by

$$ W(s) = \frac{k_p}{s + a_p} $$

where $k_p = \frac{k_m \psi_{rd}}{J}$ and $a_p = \frac{B}{J}$ are known with uncertainties and change depending on the operating point. The plant has only one input $u = i_{sq}$ and one output $y = \omega$.

The motor desired performance in the MRAC is defined by a reference model. The transfer function to the reference model is given by

$$ M(s) = \frac{k_m}{s + a_m} $$

with $r$ as input and $y_m$ as output. The gains $k_p$ and $k_m$ should have the same sign (positive, for simplicity). The goal of the MRAC is that the plant follows the model (matching condition).

If the plant parameters are known, there are controller parameters $\theta_1^*$ and $\theta_2^*$ such that the plant matches the model reference exactly. On the other hand, if these parameters are unknown or known with uncertainties is necessary to have an adaptation for the controller parameters. In the MRAC the control signal $u$ is given by

$$ u = \theta_1 y + \theta_2 r $$

and the adaptation law is ($\sigma > 0$, $\gamma > 0$)

$$ \dot{\theta}_1 = -\sigma \theta_1 - \gamma e_0 \omega_{reg} $$

where

$$ e_0 = y - y_m $$

$$ \theta = [\theta_1, \theta_2]^T $$

$$ \omega_{reg} = [y, r]^T $$

In this case, the algorithm is based on parameter estimation and it has integral adaptation laws with $\sigma$-modification to improve robustness to unmodeled dynamics and external disturbances.

### 3.2 VS-MRAC controller

In the VS-MRAC we use the same control structure of the MRAC with a switching control signal, as in the variable structure systems. Here, the sliding surface is defined by $e_0 = 0$ and the sliding condition is $e_0 \dot{e}_0 < 0$.

The integral adaptation laws are changed by switching laws as in Eq. (10), where $\theta_1$ should be calculated to take into account the uncertainties in the plant parameters. However, the main disadvantage of the VS-MRAC is the switching of the control signal with a high enough frequency (chattering).

$$ \theta_i = -\theta_i \text{sgn}(e_0 \omega_{reg,i}), \quad \theta_i > |\theta_i^*|, \quad i = 1, 2 $$

### 3.3 Dual-Mode controller

The dual-mode controller proposes a liaison between MRAC and VS-MRAC [6,7,9]. Consider the following adaptation law

$$ \mu \dot{\theta}_1 = -\sigma \theta_1 - \sigma \gamma_i e_0 \omega_{reg,i} $$

where

$$ \gamma_i = \frac{\theta_i}{|e_0 \omega_{reg,i}|}, \quad \theta_i > |\theta_i^*|, \quad i = 1, 2 $$

If $\mu \to 0$ then, in the limit, one obtains the VS-MRAC adaptation law (10). If $\mu = 1$, the Eq. (11) is the conventional MRAC adaptation law with $\sigma$-factor and a normalization (13).

$$ \dot{\theta}_1 = -\sigma \theta_1 - \sigma \gamma_i e_0 \omega_{reg,i} $$

**IV. DUAL-MODE CONTROLLER PARAMETER $\mu$**

In this section we use fuzzy logic in the evaluation of the $\mu$ parameter for the dual-mode adaptive robust controller (Fig. 1). We decided to use the TVFI method (Truth Value Flow Inference), with trapezoidal membership func-
Fuzzy +

The weights are the output singletons

tedents of each rule are associated to the minimum op-

method applied to TVFI, given by Eq. (14), where the an-

output is already the value of output

and

respectively.

results we obtain the rule set showed in Table 1.

The labels for the input variables

and the controller approximates the MRAC. The interme-

diary transitions are analysed considering the error behavior,

that is, its amplitude (specified by

) and the intensity of its variation (specified by

). Based on these simulation results we obtain the rule set showed in Table 1.

Since the inference method used is TVFI, the output

labels

, and

are represented by singletons

, and

, respectively. In the TVFI method the inference output is already the value of output

which will be sent to the dual-mode control algorithm.

The defuzzification is obtained using the centroid

method applied to TVFI, given by Eq. (14), where the antecedents of each rule are associated to the minimum operator and the weights are the output singletons

, and

, if the consequent of each rule is

, or

, respectively.

The rule set is represented by a matrix where each line has the error

labels and each column has the error deriva-

tive

labels. The numbers 1, 2, and 3 are assigned to the labels

, and

, respectively.

V. DRIVER SYSTEM

The driver system used to implement the dual-mode adaptive robust controller is composed by a four-pole, 60Hz, 1725rpm, squire cage-type, 0.25HP induction motor fed by a three-phase VSI/PWM inverter with current control by hysteresis window. In the current control, Hall effect sensors are used to measure the currents of two phases of the motor. A microcomputer receives the motor speed using a tachometer and, by a control software in C language, sends the necessary signal to the inverter. A mechanical load simulates disturbances. The nominal values of the motor are: \( J = 5 \times 10^{-3} \text{kg} \cdot \text{m}^2 \), \( B = 5.65 \times 10^{-3} \text{kg} \cdot \text{m}^2/\text{s} \), \( K_e = 21.8 \) and \( \psi_{cd} = 87.1 \times 10^{-3} \text{webers} \).

VI. SIMULATION RESULTS

Considering the rotor flux constant and the motor parameters as given in [9], then the following nominal model for the motor is obtained

\[
W(s) = \frac{3798}{s + 11,2}
\]

The reference model was considered as

\[
M(s) = \frac{12}{s + 12}
\]

With the specification of the plant model and the reference model, some simulations were carried out with the three proposed algorithms (MRAC, VS-MRAC, and Dual-Mode). A constant disturbance with 30% of the motor nominal load was introduced at the instant \( t = 0.2 \text{s} \) and the initial motor speed was considered 90rad/s. The results are showed below.

6.1 MRAC algorithm

In this simulation we use the MRAC algorithm with \( \sigma \)-modification which has the adaptation law given by Eq. (6). We use \( \sigma = 1.667 \) and \( \gamma = 0.001 \). The plant speed \( y \) and the model reference output \( y_m \) in rpm are plotted at the top of the Fig. 3. The control signal \( u \) (given in ampere (A)) is at the bottom of the Fig. 3.

<table>
<thead>
<tr>
<th>( E_{dej} )</th>
<th>( d_e \rightarrow )</th>
<th>S</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>L</td>
<td>M</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>
6.2 VS-MRAC algorithm

Using the matching condition we can calculate the parameters $\theta_1^* = -1.8 \times 10^{-4}$ and $\theta_2^* = 3.5 \times 10^{-3}$. Then, we use $\bar{\theta}_1 = 2 \times 10^{-4}$ and $\bar{\theta}_2 = 4.0 \times 10^{-3}$. The results are shown in Fig. 4. At the top are the plant $y$ and the reference model $y_m$ outputs and at the bottom is the control signal $u$.

6.3 Dual-mode algorithm

In this simulation we consider $\sigma = 1.667$ and we use fuzzy logic to calculate parameter $\mu$. The Fig. 5 shows the simulation result using the dual-mode algorithm. At the top are the plant $y$ and the reference model $y_m$ outputs, at the middle is the control signal $u$, and at the bottom is the parameter $\mu$.

VII. EXPERIMENTAL RESULTS

In the practical test the motor and the reference model outputs start with zero initial speed. The reference is initially assumed as 1000rpm, after a certain time it is increased to 1200rpm, next it is reduced to 800rpm and finally it is returned to 1000rpm. After that, it is introduced a 30% nominal load disturbance by some seconds. The experimental result is showed in the Fig. 6, where the plant and reference model speeds are given in rpm and the control signal $u = i_{sq}$ is given in mA.

VIII. CONCLUSION

A dual-mode controller to the induction motor speed control was proposed. The concept of fuzzy logic was used with the aim to get the tuning of the dual-mode controller parameter $\mu$. The main idea was the formalization of the intuition about the $\mu$ parameter behavior in each characteristic situation. According to simulations, it can be verified that the dual-mode algorithm provided a fast transient without oscillations and a smooth steady-state control signal. Additionally, it presented robustness to uncertain parameters and disturbances.
REFERENCES