# Modeling and Simulation of Variable Speed Drive System with Adaptive Fuzzy Controller Application to PMSM

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***Abstract-*** **Many industrial applications require new control techniques in order to obtain fast response and to improve the dynamic performances. One of the techniques used, is the fuzzy logic control which is characterized by robustness and insensitivity to the parameters variation. In this paper, the technique is applied for the design of a drive system fed from indirect power electronics conversion.The adaptive fuzzy controller (AFC) is applied in all regulation loops, starting from speed regulation of permanent magnet synchronous machine (PMSM) until the minimization of harmonics introduced by the line converter, including the control of power factor and DC-link voltage. We study the robustness of the controller using simulation results for different operating modes and parameters variation.**

## I. INTRODUCTION

In recent years, the permanent magnet synchronous motors (PMSM) are more and more used in high performance industrial drive systems ranging from small servo drives to high machine tool drives. The main reason of the increasing interest is their high power/weight ratio and the higher power factor. However, the PMSM presents a coupled nonlinear multivariable control structure which calls for complex nonlinear design in order to get good dynamic performance [1], [2], [3]. Moreover, the performances must be insensitive to the drive and load parameter variation vector control is typically used in these drives to improve the dynamic response and give the performance characteristics similar to that of a DC machine which are desirable in certain applications. The high performance drive systems necessitate quickly response and robustness to parameters variation. The conventional regulators can not filling this operating condition. To overcome this problem, modern regulators are used, like fuzzy logic controller. [4], [5].

The power converter connected to the line is usually used for both last drive cases as the well known three phase diode-bridge rectifier. In this converter, the power can only flow from the utility AC side to the DC side and the line current is not continuous. Because this type of AC-DC conversion does not controlled line current harmonics, the displacement power factor is poor and the DC side voltage is not constant[5 ], [6]. To remedy these disadvantages, a solution is a reversible converter to replace the diode-bridge rectifier and to permit a reversible power line flow which allows the energy recovered from motor-load inertia to be fed back to the utility supply [8 ], [9].The DC-link voltage can be regulated by fuzzy logic controller.

In this paper, an adaptive fuzzy controller is applied in all regulation loops, starting from speed regulation of permanent magnet synchronous machine until the minimization of harmonics introduced by the line converter, including the control of power factor and DC-link voltage. We study the robustness of the controller using simulation results for different operating modes and parameters variation.

## II. Model of the PMSM

Using the stator d-q equations in the synchronous reference frame the machine can be represented as:

$$\begin{aligned} v_{qs} &= R_s.i_{qs} + p\phi_{qs} + \omega_s.\phi_{ds} \\ v_{ds} &= R_s i_{ds} + p\phi_{ds} - \omega_s\phi_{qs} \end{aligned} \tag{1}$$

The developed electromagnetic torque is given as:

$$T_e = P(\phi_{af}.i_{qs} + (L_{ds} - L_{qs})i_{ds}.i_{qs}) \tag{2}$$

The interaction between electromagnetic torque and the mechanical part is given as:

$$T_e - T_l = Jp\Omega + B\Omega \tag{3}$$

In vector controlled PMSM, the motor currents are decomposed into $i_{ds}$ and $i_{qs}$ components which are respectively flux and torque components. In the case of sinusoidal fed PMSM, the orientation of the stator current gives a highly desirable characteristic. By neglecting the flux weakening effect for the low speed operation, the reference direct axis current $i_{ds}^*$ becomes zero and the maximum torque is obtained.

The developed electromagnetic torque is then given:

$$T_e = P\phi_{af}i_{qs} \tag{4}$$

and the d axis stator flux linkage is given as:

$$\phi_{ds} = \phi_{af} \tag{5}$$

The operation of the drive is then similar to that of a current controlled DC motor.

## III. CIRCUIT CONFIGURATION

The proposed system configuration is shows in Fig.1. The first controller (AFCS) is related to speed loop, its inputs are speed

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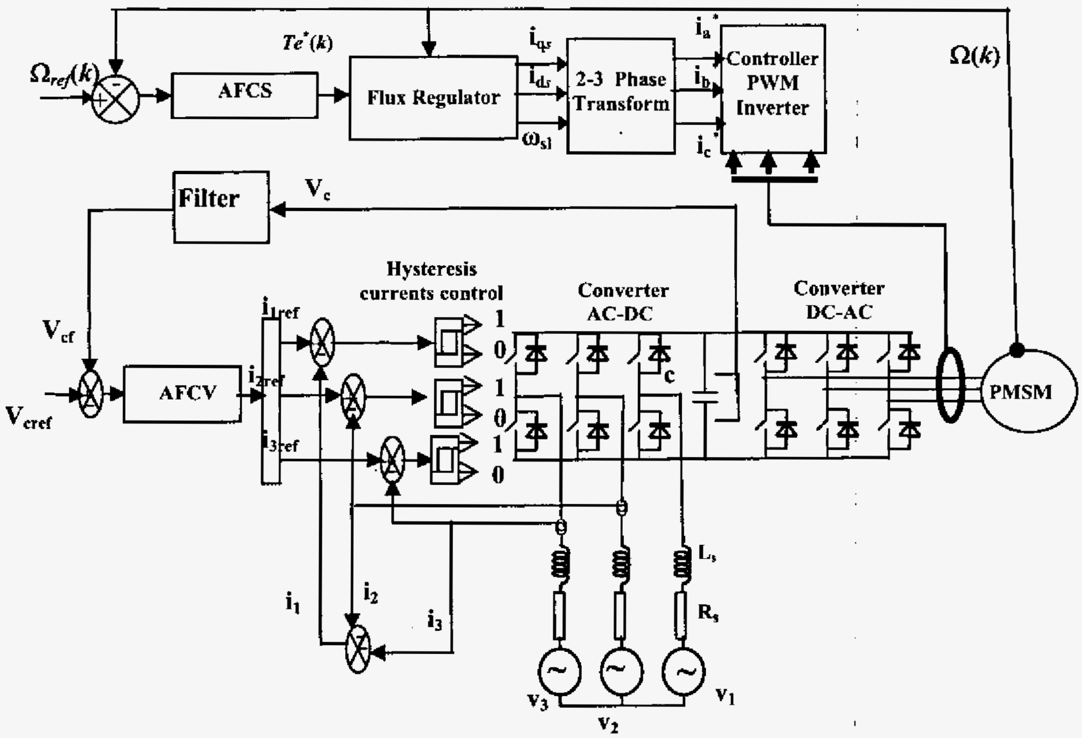

Fig.1. Main circuit with proposed control system.

error and the change of speed error and generate the reference electromagnetic torque. The second controller (AFCV) is related to voltage loop, whose inputs are the error voltage and its variation. The output of the AFCV is reference current.

## IV. CONTROL STRATEGY

The proposed control system shown in Fig. 1, it's composed by:

### A. *Fuzzy Voltage Control*

The control of DC-voltage consists of two parts:

*1. DC voltage control*

The block diagram of fuzzy logic DC-link voltage control is shown in Fig.2 . The fuzzy controller is constituted by for stages: fuzzification, rules execution, defuzzification and adaptation mechanism of the gain.

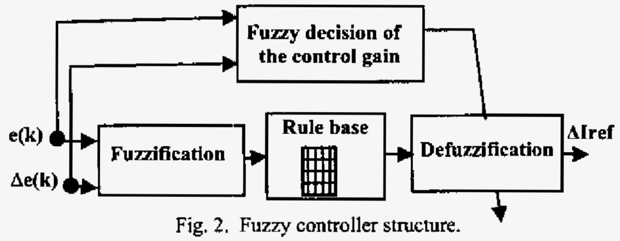

Fig. 2. Fuzzy controller structure.

The rule base is the principal component of the fuzzy controller; it indicates how the controller behaves to response to any input situation. The rule base is constituted by collection of If-Then rules of the form:

$$R_j : If\ e(k)\ is\ A_j\ and\ \Delta e(k)\ is\ B_j\ Then\ I_{ref}(k)\ is\ C_j \qquad j = 1..m \tag{6}$$

where $A_j$, $B_j$ and $C_j$ are fuzzy sets such as: NL (negative large), NM (negative medium), etc. defining fuzzy partition on the controller input space .With e($k$) and $\Delta$e($k$) are scaled and normalised version of the error $e_v(k)$ and the change of error $\Delta e_v(k)$ given by:

$$\begin{aligned} e_v &= v_{cf}(k) - v_{cref}(k) \\ \Delta e_v &= e_v(k) - e_v(k-1) \end{aligned} \tag{7}$$

where

$$\begin{aligned} e(k) &= ge.\ e_v(k) \\ \Delta e(k) &= gce.\ \Delta e_v(k) \end{aligned} \tag{8}$$

with ge and gce, constant inputs gain which play an essential role, since they determine the control performances. The expression "*e*(*k*) *is* $A_j$" is implemented by membership function indicating the grade of membership of *e*(*k*) in the fuzzy set $A_j$, this operation is called fuzzification. The shape of the membership function is quite arbitrary and depends on the user's preference. For simplicity, triangular and trapezoidal shapes are usually used. The logical operators "*and*" and "*Then*" can be interpreted as *min* or algebraic product, and various inference and defuzzification algorithms can be used to produce crisp output value. If the operators "*and*" and "*Then*" are implemented as algebraic product, the max-product inference and the center of gravity defuzzification methods are adopted in this paper.

In most fuzzy control studies, the gain associated with the control output must be constant and as low possible in order to a void the instability problem. This increases considerably the response time of the system. To solve this problem, we consider the output gain as a fuzzy variable. Therefore the gain must be adapted at every situation of the system as a function of the error and its variation. We chose fuzzy sets of variable gain whose corresponding membership functions is represented by Fig.3. The decision matrix on the control gain is given in table I.

### 2. *Calculation of Reference Current*

The amplitude of the reference current is given by the following equation:

$$I_{ref}(k) = I_{ref}(k-1) + g_u(k).\Delta I_{ref}(k) \tag{9}$$

If a sinusoidal line current is required, the current command (reference) should have the form:

$$I_{i\,ref}(k) = I_{ref}(k)\sin\left(\omega t - (k-1)\frac{2\pi}{3}\right) \tag{10}$$

with i=1,2, or 3.

To obtain a very fast of the input converter, a hysteresis current technique can be adopted, which ensures that each line current follows its reference within the hysteresis band Δi The AC line current is controlled by the transistors converter in a bang-bang mode. A high switching frequency is given by the following equation:

$$f_{\max} = \frac{U_{\max}}{8L_s\Delta i} \tag{11}$$

where

$U_{\max}$: max value of line to line supply voltage.

$L_s$: the AC side inductance.

Δi: hysteresis band.

The achievable bandwidth of the current control loop depends on the switching frequency of the PWM converter.

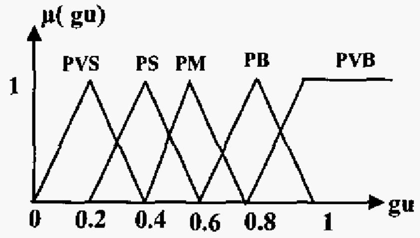

Fig. 3. Membership functions of the output gain.

TABLE I
Decision Control Gain

| e / Δe | **NB** | **NM** | **NS** | **ZE** | **PS** | **PM** | **PB** |
|---|---|---|---|---|---|---|---|
| **NB** | PVB | PVB | PB | PM | PS | PVS | PVS |
| **NM** | PVB | PB | PM | PS | PVS | PVS | PVS |
| **NS** | PB | PM | PS | PVS | PVS | PVS | PS |
| **ZE** | PM | PS | PVS | PVS | PVS | PS | PM |
| **PS** | PS | PVS | PVS | PVS | PS | PM | PB |
| **PM** | PVS | PVS | PVS | PS | PM | PB | PVB |
| **PB** | PVB | PVB | PS | PM | PB | PVB | PVB |

### B. *Fuzzy Speed Control*

To control the speed of PMSM using the fuzzy logic control, the input variables, are the speed error *e(k)* and the error change Δ*e(k)* defined as :

$$\begin{aligned} e(k) &= \Omega_{ref}(k) - \Omega(k) \\ \Delta e(k) &= e(k) - e(k-1) \end{aligned} \tag{12}$$

In loops speed regulation, we considerate the same strategy proposed for DC-voltage control. The output of AFCS can be calculated by:

$$T_e^*(k+1) = T_e^*(k) + g_u(k).\Delta T_e^*(k) \tag{13}$$

$g_u$: variable gain.

$\Delta T_e^*$: output of the AFCS.

## V. SIMULATION RESULTS

Simulation results for modeling and simulation of variable speed drive system with adaptive fuzzy controller are represented.

### A. *Speed control*

The performances of AFC of PMSM speed is compared to conventional PI regulator by extensive simulation for various operating conditions and parameters variation. The coefficients of the designed PI are $k_p$=2.3; and $k_i$=782.22. Fig.4, illustrate the results of speed response for $\Omega_{ref}$ =100 rad/s. It can be seen that the AFCS provides mush fast and robust speed response compared to the PI. When the inertia moment change from $J_n$ to $4.J_n$ , the response time with PI regulator (see Fig.5) is affected considerably compared with time response of AFCS (see Fig.6).

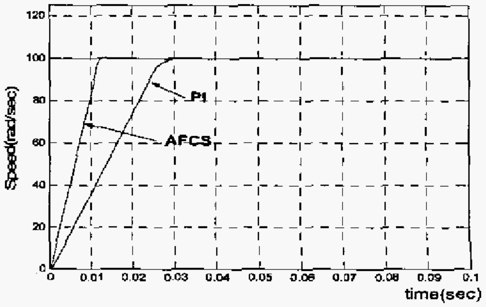

Fig.4 Simulation results with AFCS and PI controller.

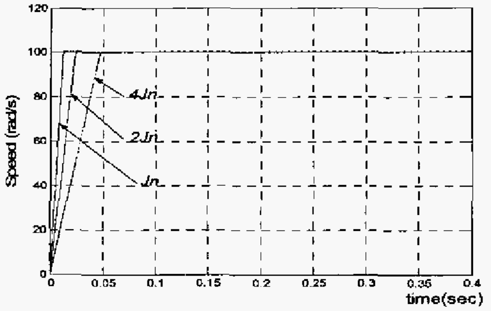

Fig.5 Simulation results for different values of $J_n$ with AFCS.

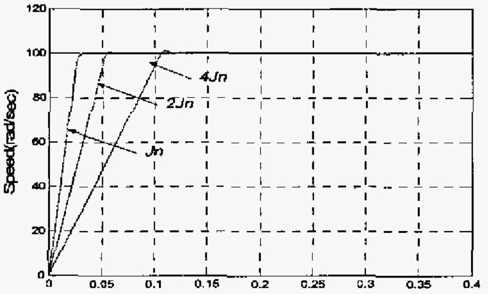

Fig.6 Simulation results for different values of $J_n$ with PI controller.

### B. Voltage control

For the control of DC output voltage using AFC, several tests have been performed in order to prove the efficiency of the proposed control.

First, the results show, after a rapid transient response due to the starting of the machine, that the DC voltage is regulated well around the reference $V_{cref}$= 240V (see Fig. 7). The input current has a sinusoidal form and in phase with supply voltage (sees Fig.8), witch minimizes the harmonics and reactive power consumed by the rectifier (see Fig. 9).In Fig 10, the power facto is near unity.

Second, to confirm the effectiveness of the proposed control, a double change of the reference is shown 240-260 and 220V. It can be noted that after the transient response, the DC voltage follows its reference; there is no overshoot and the settling time is very small (see Fig. 11).

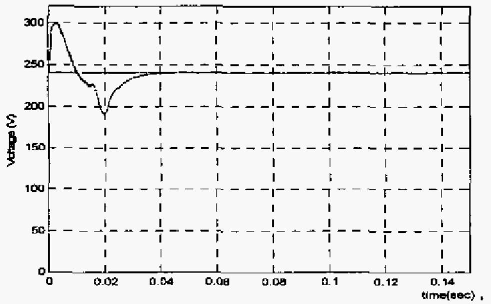

Fig. 7. DC link voltage.

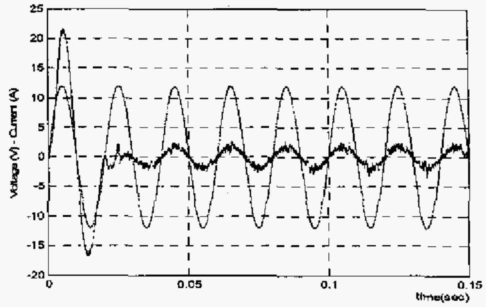

Fig 8. Line voltage ($V_l$*10) and supply current.

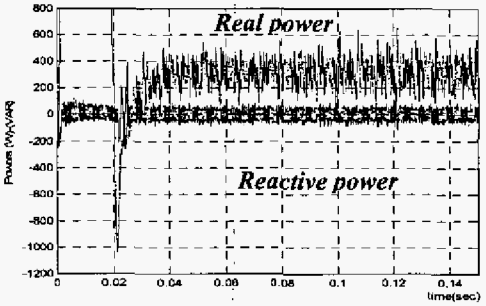

Fig. 9 Input real and reactive powers.

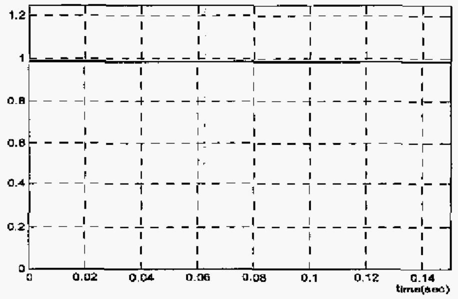

Fig. 10 Power factor.

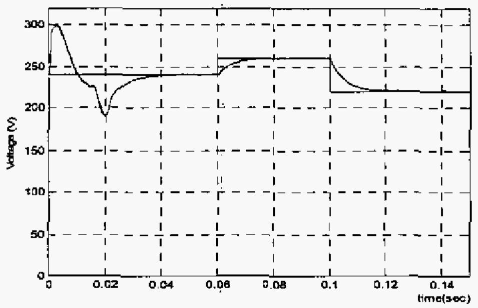

Fig. 11 DC link voltage.

## VI. CONCLUSION

In this paper, the fuzzy adaptive controller is applied in all regulation loops, starting from speed regulation of PMSM until the minimization of harmonics introduced by the line converter, including the control of power factor and DC-link voltage.

Several tests have been performed in order to prove the efficiency of the type of the control. The Simulation has confirmed the validity of this technique. It can be readily implemented using conventional microprocessors or microcontrollers.

## APPANDIX

*1. Values of the PMSM.*

| Parameter | Value |
|---|---|
| $P_n$ | 1Kw |
| $V_n$ | 120 V |
| $R_s$ | 1.4 Ω |
| $L_{ds}$ | 6.6mH |
| $L_{qs}$ | 5.8mH |
| $L_{md}$ | 5 mH |
| $L_{mq}$ | 5.8mH |
| J | 0.00176 kg.m$^2$ |
| B | 0.00038818 Nm/rd/s |
| P | 3 |
| $\phi_{af}$ | 0.1546 Wb |

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