# Two Types of Fuzzy Logic Controllers for the Speed Control of the Doubly-Fed Induction Machine

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***Abstract*—The paper presents two fuzzy logic control algorithms: type-1 and type-2. These two nonlinear techniques are used for adjust the speed control with a direct stator flux orientation control of a doubly fed induction motor. The effectiveness of the proposed control strategy is evaluated under different operating conditions such as of reference speed and for load torque step changes at nominal parameters and in the presence of parameter variation (stator resistance, rotor resistance and moment of inertia). The results of the simulation of the doubly fed induction motor velocity control have shown that fuzzy type-2 ensures better dynamic performances with respect to fuzzy type-1 control, even by parametric variations and external disturbances.**

***Index Terms*—induction motors, fuzzy logic, fuzzy control, velocity control, regulators, stability.**

## I. Introduction

Since the early years of industrialization, the researchers were faced with "how to control the electric machines at variable speed." Electric drives require high performance, increased reliability, and reduced cost [1]. Among these machines is doubly fed induction machine (DFIM) [2, 3]. is an asynchronous machine with wound rotor which can be supplied at the same time by the stator and the rotor with external source voltages [4, 5, 6].

The tree-phase induction machine powered by a voltage inverter is a drive system with two main advantages: a simple, robust and inexpensive machine structure and efficient control techniques. However, this converter-machine assembly is used only at the lower limit of the high power range (up to a few MW) due to the electrical stresses experienced by the semiconductors and their low switching frequency [7].

In the field of high power drives, one of the best solutions is the doubly-fed induction machine (DFIM) [7, 8] that becomes very popular since certain advantages compared to other types of electrical machines, especially when operating at variable speed [2].

Due to the coupling between the flux and the electromagnetic torque, the DFIM is non-linear but the vector control and the field oriented control allow a torque-flux decoupling [2, 8].

In the area of the control of the electric machines, the research works are oriented more and more towards the application of the modern control techniques [9]. These techniques involve in a vertiginous way with the evolution of the computers and power electronics. This allows to lead to the industrial processes of high performances [9, 10, 11]. These techniques are the fuzzy control, the adaptive control, the sliding mode control etc [12,13].

Fuzzy theory was first proposed and investigated by Prof. Zadeh in 1965. The Mamdani fuzzy inference system was presented to control a steam engine and boiler combination by linguistic rules. Fuzzy logic is expressed by means of if-then rules with the human language [14, 15].

Fuzzy logic control is a technique of incorporating expert knowledge in designing a controller. Past research of universal approximation theorem shown that any nonlinear function over a compact set with arbitrary accuracy can be approximated by a fuzzy system [14].

Fuzzy logic has proven to be a potent tool in the sliding mode control of time-invariant linear systems as well as time-varying nonlinear systems [16]. It provides methods for formulating linguist rules from expert knowledge and is able to approximate any real continuous system to arbitrary accuracy. Thus, it offers a simple solution dealing with the wide range of the system parameters.

The fuzzy logic theory allows the representation and processing of imprecise or approximate knowledge. Due to the fact that fuzzy logic is usually expressed by linguistic rules of IF-THEN form, it is used to solve the problems of decisions in control or to describe the dynamic behavior of an unknown or ill-defined system [17, 18].

The classical fuzzy logic called today fuzzy logic type-1 has been generalized to a new fuzzy logic called fuzzy logic type-2. In recent years, many researchers have worked on this new fuzzy logic type [19, 20], have built the theoretical foundation [21, 22].

This last fuzzy logic controller (FLC) usually gives better results for nonlinear systems with variable parameters. The DFIM is an ideal candidate for testing the performance of fuzzy logic controllers [5, 11]. Conventional type-1 fuzzy logic system can be used to identify the behavior of this highly nonlinear system with various types of uncertainties. However, type-1 fuzzy sets cannot fully capture the uncertainties in the system due to the imprecision of membership functions and knowledge base; thus, higher types of fuzzy sets have to be considered [23, 24]. It is clear that the computational complexity of operations on fuzzy sets increases with the increasing type of the fuzzy set. In this work, for their simplicity and efficiency to capture the severe nonlinearities of the DFIM, the interval type-2 fuzzy sets will be used.

Till now, type-2 fuzzy logic systems have been used in very few control applications such as nonlinear control and the speed control of machines. Nevertheless, it is still possible to achieve robustness and highly efficient dynamics using a control technique that does not need a detailed model. This is the case with the controller presented herein where an interval type-2 fuzzy logic controller is designed to achieve the speed stabilization of DFIM.

In this paper, the performances of the adaptive gain IP control of the speed of a DFIM using fuzzy logic controllers type 1 and type 2, respectively, will be compared.

## II. Dynamic Modeling of the DFIM and the Fuzzy Control

### A. Description and Modeling of DFIM

In the training of high power as the rolling mill, there is a new and original solution using a double feed induction motor (DFIM) [1, 6]. The stator is feed by a fixed network and the rotor by a variable supply which can be either a voltage or current source.

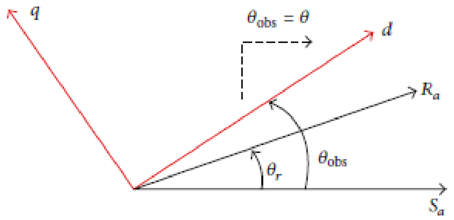



Figure 1. Defining the real axes of DFIM into the ($d$, $q$) reference frame

### B. The Mathematical Dynamic Model of DFIM

The DFIM dynamic model, expressed in the synchronous reference frame (Fig. 1) is given by the voltage equations [5, 8]:

$$\bar{V}_s = R_s \bar{I}_s + \frac{d\bar{\Psi}_s}{dt} + j\omega_s \bar{\Psi}_s \tag{1a}$$

$$\bar{V}_r = R_r \bar{I}_r + \frac{d\bar{\Psi}_r}{dt} + j\omega_r \bar{\Psi}_r \tag{1b}$$

The fluxes are expressed by:

$$\bar{\Psi}_s = L_s \bar{I}_s + M_{sr} \bar{I}_r \tag{2a}$$

$$\bar{\Psi}_r = L_r \bar{I}_r + M_{sr} \bar{I}_s \tag{2b}$$

From (1) and (2), the current state model may be written:

$$\frac{d\bar{I}_s}{dt} = -\frac{R_s}{\sigma L_s}\bar{I}_s + \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{I}_r + \frac{1}{\sigma L_s}\bar{V}_s - \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{V}_r \tag{3a}$$

$$\frac{d\bar{I}_r}{dt} = -\frac{R_r}{\sigma L_r}\bar{I}_r + \frac{M_{sr}R_s}{\sigma L_s L_r}\bar{I}_s + \frac{1}{\sigma L_r}\bar{V}_r - \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{V}_s \tag{3b}$$

The mechanical equation is expressed by:

$$\frac{J}{p}\frac{d\omega}{dt} = C_e - \frac{k_f\,\omega}{p} - C_r \tag{4}$$

The electromagnetic torque is given by:

$$C_e = p\,M_{sr}\,\mathrm{Im}\left(\bar{I}_s \bar{I}_r^*\right) \tag{5}$$

So, the speed variation equation becomes:

$$\frac{J}{p}\frac{d\omega}{dt} = p\,M_{sr}\,\mathrm{Im}\left(\bar{I}_s \bar{I}_r^*\right) - \frac{k_f\omega}{p} - C_r \tag{6}$$

### C. The Direct Stator Flux Oriented Control

The DFIM model can be described by the following state equations in the synchronous reference frame whose $d$ axis is aligned with the stator flux vector [6, 8]:

$$\Psi_{sd} = \Psi_s; \qquad \Psi_{sq} = 0; \qquad \frac{d\Psi_{sq}}{dt} = 0 \tag{7}$$

$$i_{rd} = -\frac{L_s}{pM_{sr}\Psi_s}; \qquad i_{rq} = \frac{\Psi_s}{M_{sr}} \tag{8}$$

$$\frac{d\theta_s}{dt} = \omega_s = \frac{1}{\Psi_s}\left(\frac{R_s M_{sr}}{L_s} + V_{sq}\right) \tag{9}$$

$$V_{rd} = \left(R_r + \frac{M_{sr}^2}{L_s T_s}\right) i_{rd} + \sigma L_r \frac{di_{rq}}{dt} + \frac{M_{sr}}{L_s} V_{sd} - \frac{M_{sr}}{L_s T_s}\Psi_{sd} - \sigma L_r(\omega_s - \omega) i_{rq} \tag{10}$$

$$V_{rq} = \left(R_r + \frac{M_{sr}^2}{L_r T_r}\right) i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \frac{M_{sr}}{L_r} V_{sq} - \frac{M_{sr}}{L_r}\omega\Psi_{sd} - \sigma L_r(\omega_s - \omega) i_{rd} \tag{11}$$

with: $T_s = \dfrac{L_s}{R_s}; \qquad T_r = \dfrac{L_r}{R_r}$

where the following notations have been used:
$i_{rd}$, $i_{rq}$ - rotor current components;
$\Psi_{sd}$, $\Psi_{sq}$ - stator flux components;
$V_{sd}$, $V_{sq}$ - stator voltage components;
$V_{rd}$, $V_{rq}$ - rotor voltage components;
$R_s$, $R_r$ - stator and rotor resistances, respectively;
$L_s$, $L_r$ - stator and rotor inductances, respectively;
$M_{sr}$ - mutual inductance;
$p$ - number of pole pairs;
$C_e$, $C_r$ - electromagnetic and load torque, respectively;
$J$ - inertia moment of the DFIM;
$\Omega$ - mechanical angular speed;
$\omega_s$, $\omega$ - stator and rotor angular speed, respectively;
$k_f$ - friction coefficient;
$T_s$, $T_r$ - stator and rotor time-constants, respectively.

### D. The Stator Flux Estimator

In the direct vector control stator flux oriented DFIM, precise knowledge of the amplitude and the position of the stator flux vector is necessary.

In motor mode of DFIM, the stator and rotor currents are measured whereas the stator flux can be estimated [1, 6]. The flux estimation may be obtained by the following equations:

$$\Psi_{sd} = l_s I_{sd} + M_{sr} I_{rd} \tag{12a}$$

$$\Psi_{sq} = l_s I_{sq} + M_{sr} I_{rq} \tag{12b}$$

The position of the stator flux is calculated by:

$$\theta_r = \theta_s - \theta; \quad \theta_s = \int \omega_s dt; \quad \theta = \int \omega\, dt \tag{13a, b, c}$$

$$\omega = p\Omega \tag{13d}$$

and the following notations have been used:
$\theta_s$ - the electrical stator position;
$\theta$ - the electrical rotor position.

### *E. The Fuzzy Control*

Fuzzy control can operate when the systems to be controlled are poorly known or difficult to describe precisely, or when the variables are evaluated subjectively and expressed in natural language and not numerically [25, 26]. It is simple to carry out, flexible and therefore easily adaptable to the operating conditions of the process. The rules are easy to understand and to modify since they are expressed by natural language terms [26, 27]. The internal architecture of a fuzzy controller is given in Fig. 2.

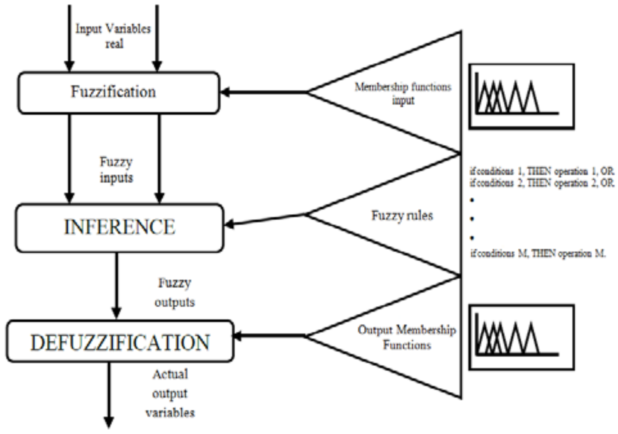



Figure 2. Structure of a fuzzy controller [28]

A fuzzy controller consists of three blocks: fuzzification, inference and defuzzification.

The **fuzzification block** performs the passage from the real quantities to the fuzzy variables by adapting the different domains corresponding to the variation of the input and output variables. For each variable its fuzzy subsets as well as their associated membership functions are defined [29, 30].

In the **inference block**, the values of the input and output language variables are linked by a table of rules that take into account the static and dynamic behavior of the system to be monitored. It is a decision-making mechanism that, by manipulating the fuzzy rules, takes a decision [31]. There are several methods of inference: Maximum-Minimum, Max-Product, Sum-Product [32]. The method name designates the operators used respectively for fuzzy rule aggregation and fuzzy implication [33]. In this paper, the sum-product method was used.

The aim of the **defuzzification block** consists of defining precisely what must be the action on the process. Indeed, the method cannot interpret linguistic orders provided by inference methods. From the resultant membership function, the defuzzification operation makes possible to calculate the real actual value of the output variable to be applied to the process. There are several methods of defuzzification: maxima method, center of gravity method, average maxima method. However, it is recognized that the center of gravity method works best. Note that normalization and denormalization blocks are added respectively to the input and output of the fuzzy controller so that it is transportable and adaptable even with different parameters [34].

## III. The Speed Control by Fuzzy Logic Type 1

The control thus obtained is an indirect vector control in which certain characteristics of the system are exploited to define the law of control which allows to guarantee the validity of the decoupled model and to obtain high dynamic performances.

### *A. Definition of Inputs and Outputs*

In the following, we are mainly interested in the speed regulator within a vector control of the asynchronous double-feed machine. The reference speed can be controlled by an external operator. The output variable of this speed controller is the image of the reference electromagnetic torque that the control-converter-machine assembly must generate. At constant flux, this torque is proportional to the current $I_{sq}^*$ imposed as an input to the current regulation loop ($I_{sq}$ - current reference).

The basic scheme of the fuzzy regulator rests on the structure of a conventional regulator except that the incremental form is retained.

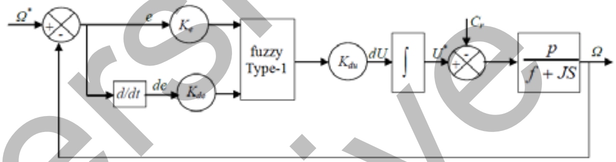



Figure 3. Structure of the PI type blur fuzzy type-1 controller

In Fig. 3 the following notations have been used:

$e(k)$ : the error, defined by:

$$e(k) = \Omega^*(k) - \Omega(k) \tag{14}$$

$\Delta e(k)$: the variation of the error, approximated by:

$$\Delta e(k) = e(k) - e(k-1) \tag{15}$$

$K_e$, $K_{de}$, $K_{du}$: normalization gains that can be constant (or variable). ($K_e = 0.1$, $K_{de} = 0.6\times10^{-5}$, $K_{du} = 65$).

The choice of the latter makes it possible to guarantee the stability and to improve the dynamic and static performances of the system to be regulated [35, 36].

The control signal is determined by:

$$C_{em}^*(k) = U^*(k) - U^*(k-1) + \Delta U^* \tag{16}$$

### *B. Definition of membership functions*

The membership functions of the input and output variables are defined by triangular and trapezoidal shapes (Figs. 4 and 5).

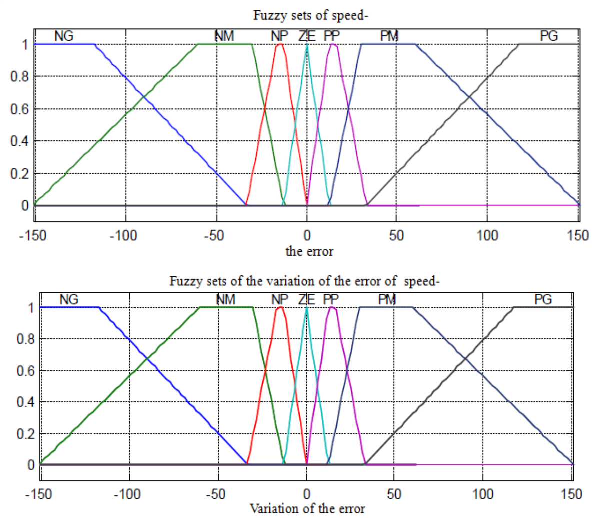



Figure 4. Input membership functions $e(k)$ and $\Delta e(k)$

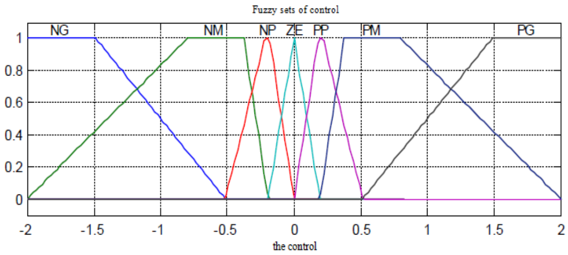



Figure 5. Output membership functions for the control

## C. *Rule Block*

The fuzzy rules are given in Table 1.

TABLE I. THE FUZZY RULES

| | $\Delta e(k)$ | | | | | | |
|---|---|---|---|---|---|---|---|
| $e(k)$ | NB | NM | NS | ZE | PS | PM | PB |
| NB | NB | NB | NB | NM | NS | NVS | ZE |
| NM | NB | NB | NM | NS | NVS | ZE | PVS |
| NS | NB | NM | NS | NVS | ZE | PVS | PS |
| ZE | NM | NS | NVS | ZE | PVS | PS | PM |
| PS | NS | NVS | ZE | PVS | PS | PM | PB |
| PM | NVS | ZE | PVS | PS | PM | PB | PB |
| PB | ZE | PVS | PS | PM | PB | PB | PB |

In this table, the following notations have been used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big), NVS (Negative Very Small), PVS (Positive Very Small).

## D. *Defuzzification*

The output of the inference mechanism is a fuzzy variable. The fuzzy function approximation must convert the internal fuzzy variables into real variables so that the system can use these variables [37, 38].

In this step, a real value of the output variable *uu* is obtained by using the method of the center of gravity.

Fig. 6 shows the relationship between the input and the output using the error as the *x*-axis, the variation of the error as the *y*-axis, and the control signal as the *z*-axis, in accordance with Table I.

## E. *Simulation results*

Fig. 7 shows the responses of the loaded DFIM after a no-load start.

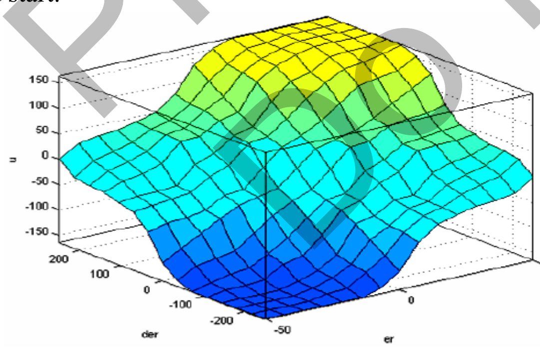
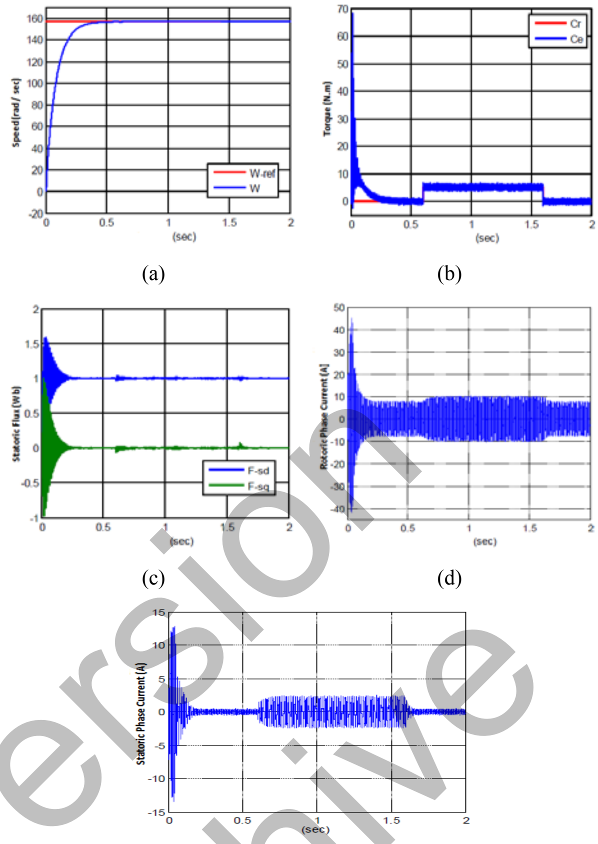



Figure 6. The relationship between the input and the output (*x*-axis - the error, *y*-axis - the variation of the error, *z*-axis - the control signal)

## A. *Robustness tests*

In order to test the robustness of the control using fuzzy logic type 1, three tests are carried out. The first is that by increasing the stator resistance, the second by increasing the rotor resistance and the third by increasing the inertia.




(a) (b) (c) (d) (e)

Figure 7. Simulation results of the fuzzy logic control type-1 applied to a no-load started DFIM, followed by the application of a load within the time interval $t = [0.6, 1.6]$ s

### *Variation in the stator resistance*

Fig. 8 illustrates the dynamic responses of velocity, electromagnetic torque and stator flux components for an increase in the value of the stator resistance by 100% of its nominal value.

### *Variation in the rotor resistance*

The performance of the fuzzy logic type 1 against the parametric drifts is tested for a variation of the rotor resistance, as illustrated in Fig. 9.

### *Variation in the moment of inertia*

Fig. 10 shows the simulation responses of the DFIM for an increase in moment of inertia of + 50% of its nominal value.

### *Comments about Results*

The results obtained show that the blurred controller used good performance not only in tracking but also in regulation, with good tracking of the reference speed, and this in all cases of profiles studied.

In Fig. 7, we see that the introduction of the load has no influence on the evolution of the speed (Fig. 7a) and also of the flux (Fig. 7c), which shows the robustness of the typical fuzzy control 1 in the face of these disturbances.

In order to test the robustness of the control by the fuzzy type-1 logic with respect to a significant variation in the stator resistance, the dynamic behavior of the DFIM was simulated with an increase in the value of the stator resistance of + 100% of its nominal value at $t = 0.6$ s.

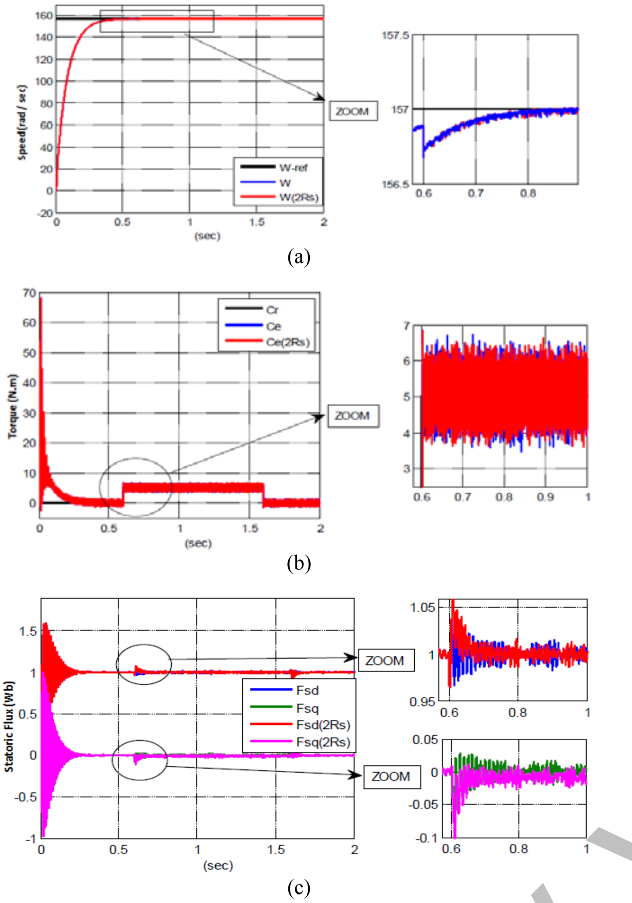



Figure 8. Robustness test of the speed control by fuzzy type-1 logic for a variation of the stator resistance $R_s$ of +100%

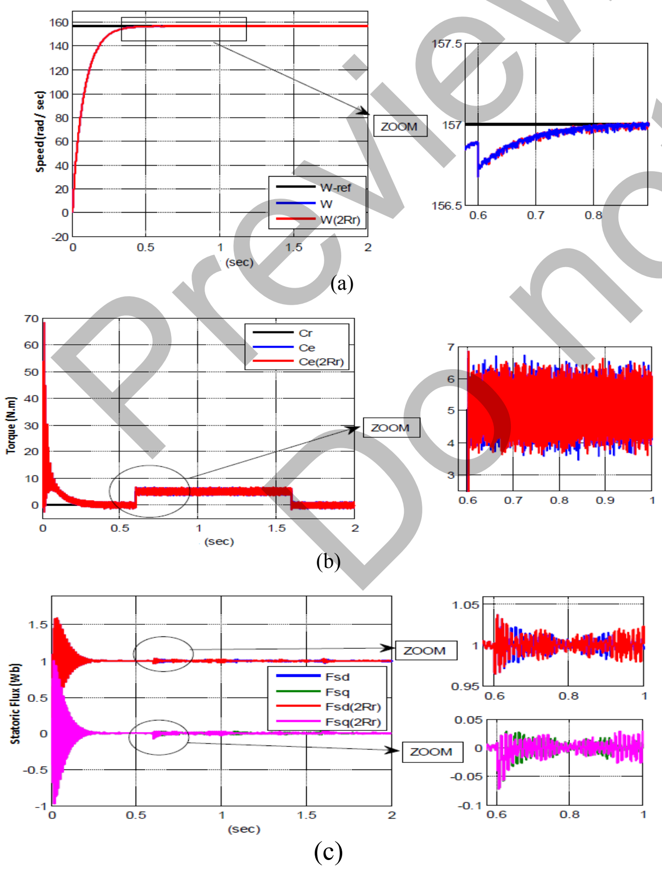



Figure 9. Robustness test of the speed control by fuzzy type-1 logic for a variation of the rotor resistance $R_r$ of + 100%

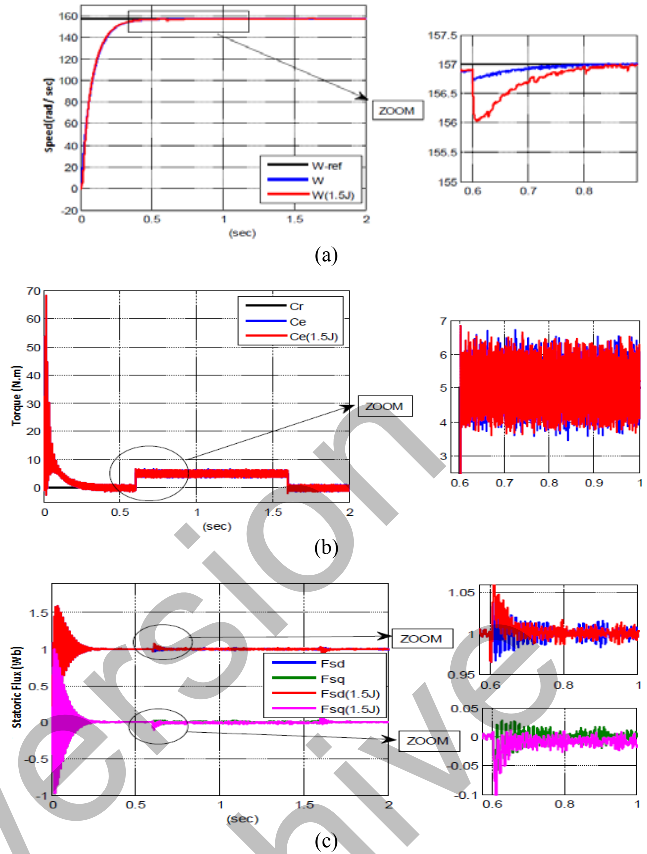



Figure 10. Robustness test of the speed control by fuzzy type-1 logic for a variation of the inertia moment $J$ of + 50%

Fig. 8 shows the simulation results obtained. In view of the results obtained, it is noted that the variation of the stator resistance does not cause any undesirable effect on all the dynamic responses (Fig. 8), and this shows the robustness of the type-1 blur controller compared to the variation of the stator resistance. Moreover, decoupling is not affected by this variation.

Fig. 9 illustrates the dynamic responses of speed (Fig. 9a), electromagnetic torque (Fig. 9b) and the components of the stator flux (Fig. 9c), for a variation of the value of the rotor resistance of 100% of its nominal value. The results obtained clearly show the robustness of the fuzzy type-1 control versus the parametric variations.

Fig. 10 presents the influence of the variation of the moment of inertia on the DFIM responses. According to the results obtained, it can be seen that increasing the moment of inertia by + 50% of its nominal value causes an increase in the response time. This shows that control by fuzzy logic type-1 loses its dynamic performance a little but it retains its robustness with respect to this parametric variation.

Finally, two major drawbacks to the control by fuzzy type-1 logic are to be noted [35]:

- the absence of theoretical methods for the synthesis of fuzzy controllers;
- the lack of appropriate formal theoretical tools for studying the stability of systems controlled by fuzzy logic.

## IV. The Speed Control by Fuzzy Logic Type 2

With the development of Type-2 Fuzzy Logic Control (T2-FLS) and considering its ability to handle uncertainty, utilizing T2-FLC has attracted a lot of interest in recent years. The concept of type-2 fuzzy sets was firstly introduced by Zadeh as an extension of the concept of well-known ordinary fuzzy sets, type-1 fuzzy sets [39, 40]. A type-2 fuzzy set is characterized by a fuzzy membership function i.e. the membership grade for each element is also a fuzzy set in [0, 1], unlike a type-1 fuzzy set, where the membership grade is a crisp number in [0, 1] [40, 41]. The membership functions of type-2 fuzzy sets are three dimensional and include a footprint of Uncertainty (FOU), which is the new third dimension of type-2 fuzzy sets. The footprint of uncertainty provides an additional degree of freedom to handle uncertainties [42, 43].

One of the most important features that differentiate T2-FLC from T1-FLC is the type of reduction process [44, 45]. Type-1 and Type-2 triangular membership functions are shown in Fig. 11.

Type-1 membership function (Fig. 10 (a)) can be expressed as follows:

$$B = (x, \mu_B(x)) \mid \forall x \in X \tag{17}$$

where $\mu_B(x)$ which represents the membership level of the variable $x$ related to the $B$ set has values between 0 and 1. The uncertainty cannot be expressed because there is a membership level between 0 and 1 for each variable $x$. If the membership level of a variable is not fully known and can not be determined, the use of the type-2 membership function is required [46, 47].

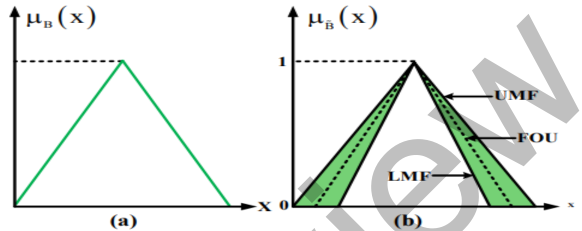



Figure 11. Triangular membership functions (a) T1FLC (b) T2FLC

The type-2 fuzzy set given in Fig. 10 (b) can be expressed by $\tilde{B}$ and can be explained by the following equations.

$$\tilde{B} = \{(x, u, (\mu_{\tilde{B}}(x,u)))\} \mid \forall x \in X, \forall u \in J_x^u \subset [0,1] \tag{18}$$

$$\tilde{B} = \int_{x \in X} \int_{u \in J_x} \mu_{\tilde{B}}(x,u)/(x,u)\, J_x \subseteq [0,1] \tag{19}$$

Here, $X$ is the domain of the input variable, $x$ is the value of the input variable, $u$ is the primary grade of a type-2 fuzzy set and $J_x$ is the primary membership of a type-2 fuzzy set, $\mu_B(x, u)$ is the secondary membership function [46].

$$\tilde{B} = \int_{x \in X} \int_{u \in J_x} 1/\mu_{\tilde{B}}(x,u)\, J_x \subseteq [0,1]$$

$$\tilde{B} = \int_{x \in X} \int_{u \in J_x} 1/\mu_{\tilde{B}}(x,u)\, J_x \in [0,1] \tag{20}$$

where, $J_x \in [0, 1]$ and the double integral indicates the union over all admissible values of $x$ and $u$.

After defuzzification process, the combination of all secondary sets can be expressed as follows:

$$\tilde{B} = \int_{x \in X} \left[ \int_{u \in J_x} f_x(u)/u \right] /x,\ J_x \subseteq [0,1] \tag{21}$$

The defuzzified type-1 membership functions do not have a uniform geometric shape. A limited area with a uniform geometrical shape named the footprint of uncertainty (FOU) is created in order to better express the membership functions. The following equation can be given for FOU.

$$\mathrm{FOU}(\tilde{B}) = \bigcup_{x \in X} J_x \tag{22}$$

The structure of the T2-FLC is similar to the T1-FLC, but the type-reducer is the difference in T2-FLC structure. Fig. 12 shows the structure of T2-FLC [48].

The fuzzifyier, (the input unit of T2-FLC), is a process of converting a corresponding linguistic variable depending on the appropriate membership function of any sharp value. The inference mechanism is a simulation of the human decision making process [49-50].

Type-reduction can be expressed as the process of finding the center of gravity of the output membership functions created for the system to be controlled [39].

In this study, triangular membership functions (Fig. 13) are preferred. Two inputs and one output are selected for designed T2-FLC. The error of speed ($e$) and the change in speed ($\Delta e$) are determined as:

$$e(k) = \omega^*(k) - \omega(k) \tag{23}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{25}$$

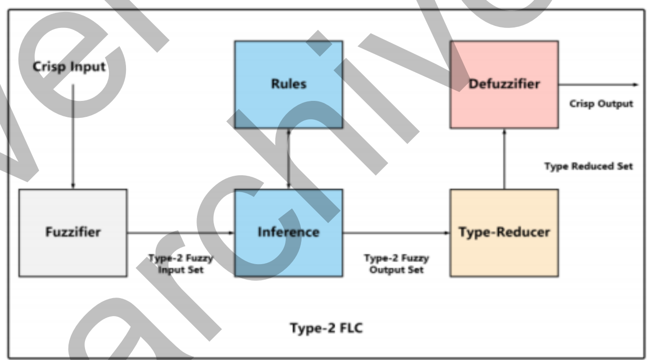



Figure 12. Block diagram of T2-FLC

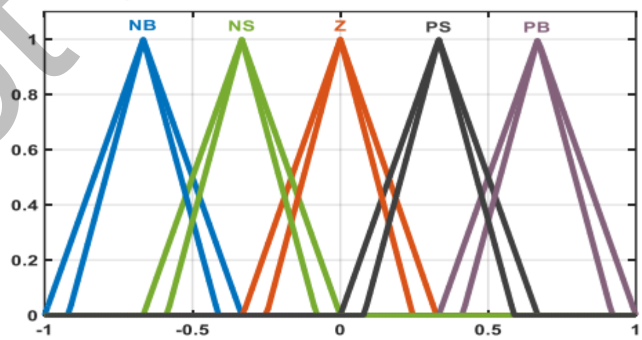



Figure 13. Triangle membership functions for inputs and output

### A. Application of fuzzy logic type-2

For the DFIM speed setting, the structure of the proposed fuzzy type-2 controller is represented in Fig. 14.

The membership functions are defined by Gaussian forms (Fig. 15). The rules table for type-2 will remain exactly the same as those for type-1. The surface generated for $\Delta K_p$ is shown in Fig. 16.

### B. Simulation results

The figures below illustrate the different simulation tests of the DFIM, by applying the fuzzy type 2 command.

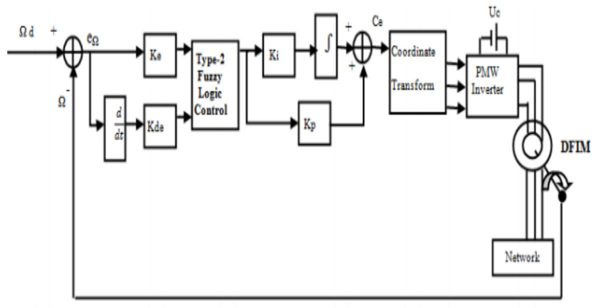



Figure 14. Structure of the PI-blur type-2 controller

Fig. 17 illustrates the behavior of the DFIM when the load is changed. From these results, it can be seen that control by fuzzy logic type-2 perform better regulation (precision and stability) of the velocity and of the stator flux, where the introduction of the charges has no influence on the evolution of speed and flow.

### *B. Robustness test*

To judge correctly this command, several tests are carried out (parametric variation of the machine).

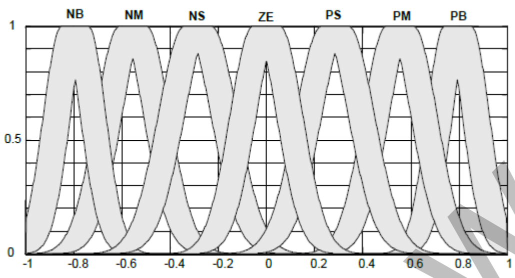



Figure. 15. Membership functions $e(k)$ , $\Delta e(k)$ and $u(k)$

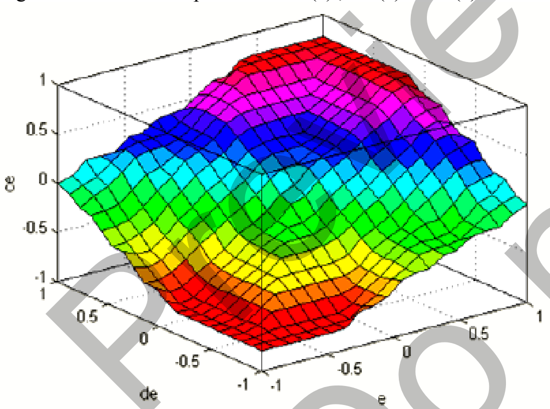



Figure 16. Surface generated for $\Delta K_P$

*Variation in the stator resistance*

Fig. 18 shows the velocity, torque and stator flux responses of the DFIM by simulation, obtained for a 100% increase in the nominal value of the stator resistance.

*Variation in the rotor resistance*

Fig. 19 illustrates the velocity, torque and stator flux responses of the DFIM when increasing the rotor resistance by + 100% of its nominal value.

*Variation in the moment of inertia*

In this test, the moment of inertia is varied by + 50% of its nominal value.

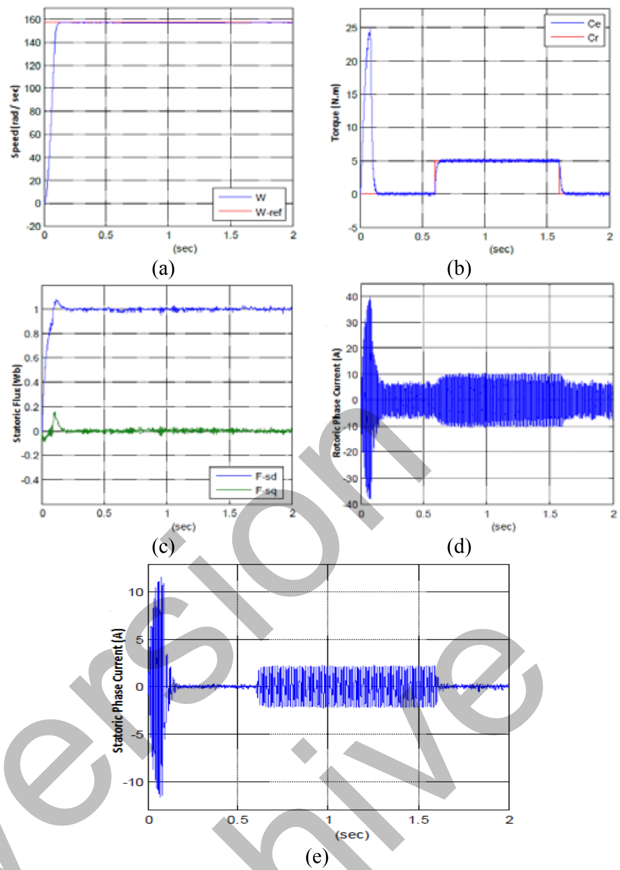



Figure 17. Simulation results of the fuzzy logic control type-2 followed by the application of a load on the interval $t = [0.6, 1.6]$ s

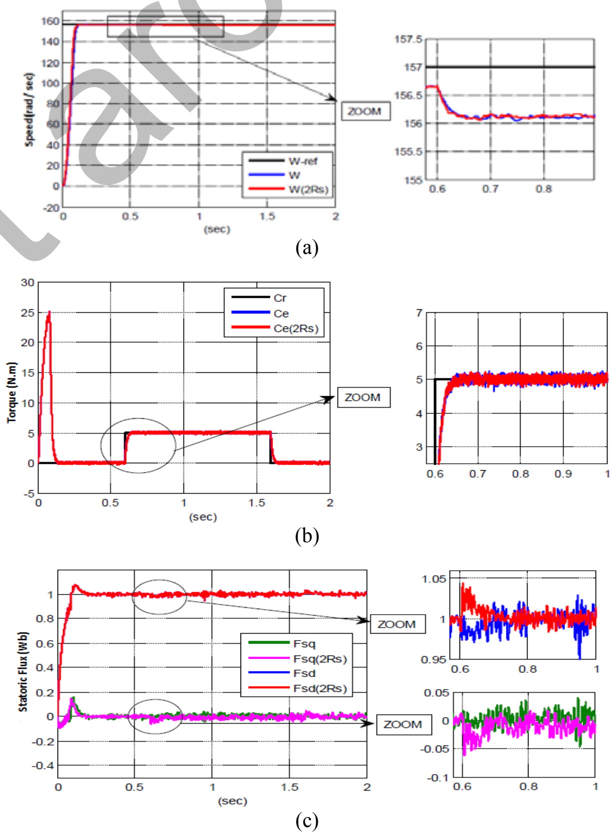



Figure 18. Robustness test of the speed control by fuzzy type-2 logic for a variation of the stator resistance $R_s$ of + 100%

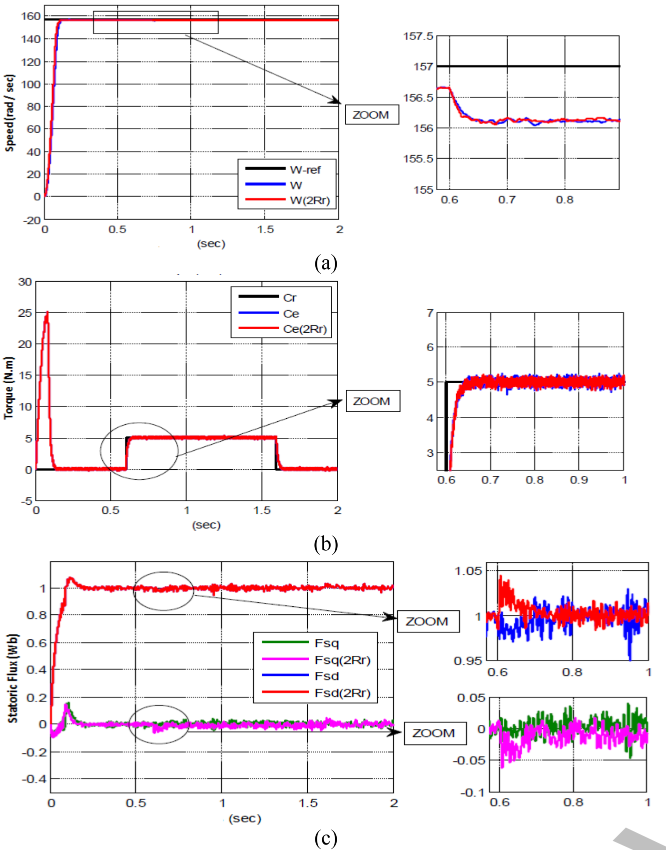



Figure 19. Robustness test for a variation of $R_r$ of + 100%, with a speed control of the DFIM by fuzzy logic type-2

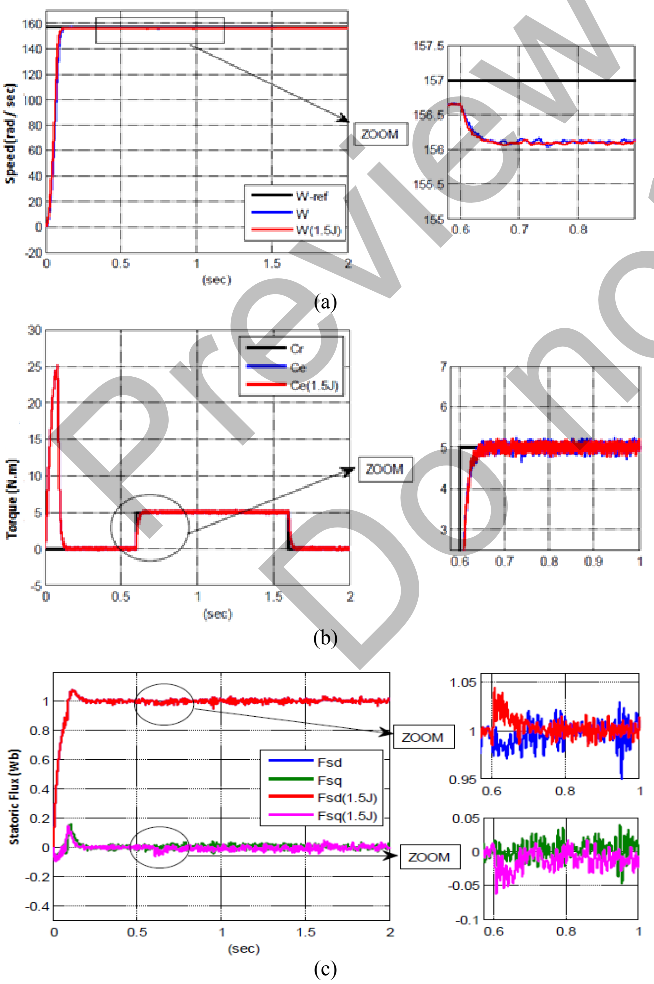



Figure 20. Robustness test of the speed control by fuzzy type-2 logic for a variation of inertia moment *J* of + 50%

Fig. 20 illustrates the velocity, torque and stator flux responses of the DFIM when the moment of inertia is increased by + 50% of its nominal value

*Comments about Results*

In Fig. 17 we may see that the control by fuzzy logic type-2 has better regulation (precision and stability) of the speed and the stator flux, where the introduction of the charges has no influence on the evolution speed (Fig. 17a) and flux (Fig. 17c).

Figs. 18 and 19 show excellent performance, not only in tracking but also in regulation, with good monitoring of the reference speed (Figs. 18a and 19a) with zero static error and response time fast compared to previous orders. Insensitivity and rejection of disturbances are excellent.

We also note that the stator flux is well achieved (Figs. 18c and 19c), moreover the electromagnetic torque represents a good response (Figs. 18b and 19b).

In Fig. 20, we may see that the increase of the moment of inertia by + 50% of its nominal value has no influence on the behavior of the machine.

So despite these variations, the fuzzy type-2 control still remains robust with decoupling always ensured.

## V. Conclusion and Future Work

The major interest in using fuzzy logic in control systems lies in its capacity to translate the control strategy of a qualified operator into a set of easily interpretable linguistic rules, which may be integrated in an automatic command system.

Unfortunately the manipulation of imprecise rules can generate a significant number of errors. Therefore, the implementation of a fuzzy system requires special attention during the test phase so as to detect any aberrations in the control system.

In this paper, two algorithms of control by fuzzy logic were presented, i.e. the fuzzy logic control type-1 and the fuzzy logic control type-2. After a short presentation of basic concepts, the two non-linear control techniques were implemented in the regulation system of the speed of a doubly fed induction machine.

The simulations results have shown that the control by fuzzy logic type-2 ensures better dynamic performance compared to the control by fuzzy logic type-1, even in the presence of parametric variations and external disturbances (stator resistance, rotor resistance and moment of inertia).

Another technique, based on the application of the adaptive control by fuzzy logic type-1 and type-2, will be analyzed and presented in a future work.

## Appendix

DFIM parameters used for simulation

| | |
|---|---|
| Rated power *P* | 5 kW |
| Stator resistance $R_s$ | 3.72 Ω |
| Rotor resistance $R_r$ | 2.12 Ω |
| Stator inductance $L_s$ | 0.022 H |
| Rotor inductance $L_r$ | 0.006 H |
| Mutual inductance $M_{sr}$ | 0.3672 H |
| Number of pole pairs *p* | 1 |
| Inertia moment *J* | 0.0662 kg m$^2$ |
| Viscous friction coefficient $f_r$ | 0.001 kg m$^2$/s |

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