# Fuzzy logic : principles and applications


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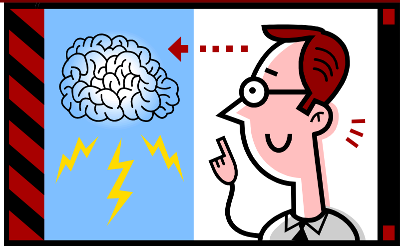
# Fuzzy Logic

## What is Fuzzy Logic?



A computational paradigm that is based on how humans think

Fuzzy Logic looks at the world in imprecise terms, in much the same way that our brain takes in information  (e.g. temperature is hot, speed is slow), then responds with precise actions.

The human brain can reason with uncertainties, vagueness, and judgments. Computers can only manipulate precise valuations. Fuzzy logic is an attempt to combine the two techniques.

“Fuzzy” – a misnomer, has resulted in the mistaken suspicion that FL is somehow less exact than traditional logic

# Fuzzy logic

## What is Fuzzy Logic?

FL is in fact, **a precise problem-solving methodology**.

It is able to simultaneously handle numerical data and linguistic knowledge.

A technique that facilitates the control of a complicated system without knowledge of its mathematical description.

Fuzzy logic differs from classical logic in that statements are no longer black or white, true or false, on or off.
In traditional logic an object takes on a value of either zero or one.
In fuzzy logic, a statement can assume any real value between 0 and 1, representing the degree to which an element belongs to a given set.

# Fuzzy Logic

## History of Fuzzy Logic

**Professor Lotfi A. Zadeh**
http://www.cs.berkeley.edu/~zadeh/

In **1965**, **Lotfi A. Zadeh** of the University of California at Berkeley published "Fuzzy Sets," which laid out the mathematics of fuzzy set theory and, by extension, fuzzy logic. Zadeh had observed that conventional computer logic couldn't manipulate data that represented subjective or vague ideas, so he created fuzzy logic to allow computers to determine the distinctions among data with shades of gray, similar to the process of human reasoning.

**Source: August 30, 2004** [(Computerworld)](http://www.computerworld.com/news/2004/story/0,11280,95282,00.html)

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# Task 1

1) What is the principle of fuzzy logic? Explain the distinction between it and classical logic.

Fuzzy logic is a concept of ‘certain degree’. Boolean logic is a subset of fuzzy logic.

Fuzzy logic is a form of many-valued logic which deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets (where variables may take on true or false values), fuzzy logic variables may have a truth value that ranges in degree between 0 and 1.

2) What is the main difference between the probability and fuzzy logic?

Probability is ADDITIVE, means all its values must add up to one. This is main difference between fuzzy logic and probability. Although both probability and fuzzy logic contain values between the range of 1 and 0, fuzzy logic tells the extent of a specific member function, whereas probability gives the frequency, hence all values of its set must add up to one.

# Task 1

3) What is the reasons that fuzzy logic has rapidly become one of the most successful technology for developing sophisticated control systems?

Fuzzy logic is conceptually easy to understand.

Fuzzy logic is flexible.

Fuzzy logic is tolerant of imprecise data.

Fuzzy logic can model nonlinear functions of arbitrary complexity.

Fuzzy logic can be built on top of the experience of experts.

Fuzzy logic can be blended with conventional control techniques.

Fuzzy logic is based on natural language.

# Task 1

4) When not to use fuzzy logic?

When a simpler solution already exists.

5) Give at least 3 famous applications of fuzzy logic.

- Nissan – fuzzy automatic transmission, fuzzy anti-skid braking system
- CSK, Hitachi – Hand-writing Recognition
- Sony - Hand-printed character recognition
- Ricoh, Hitachi – Voice recognition.

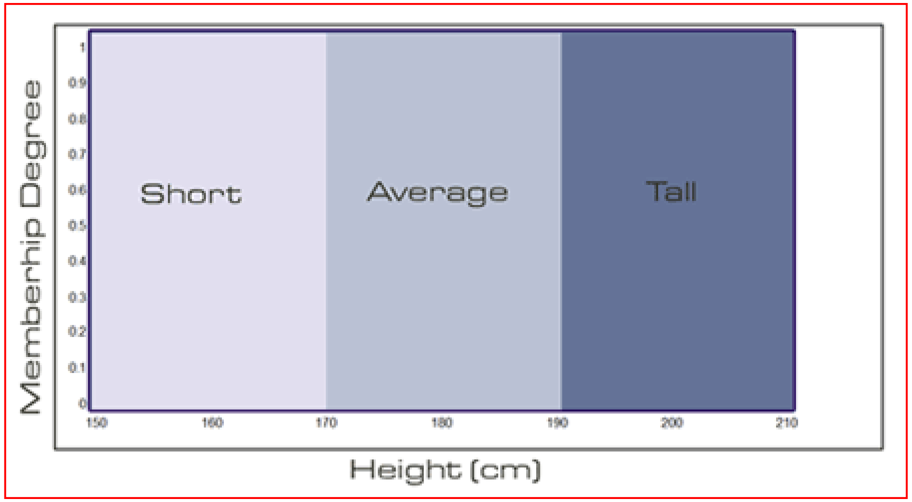
# Fuzzy Logic Explained

## Fuzzy Set Theory

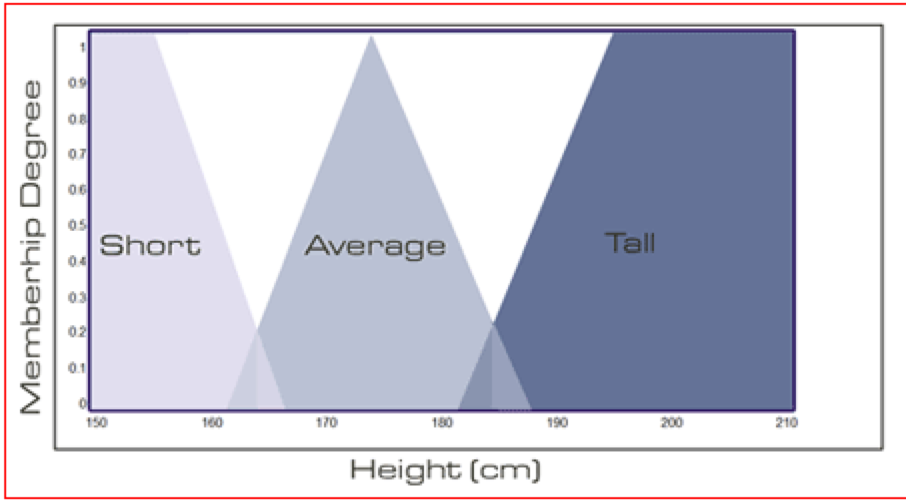
Is a man whose height is 180 cm average or tall?

A fuzzy system might say that he is partly medium and partly tall.

Boolean representation

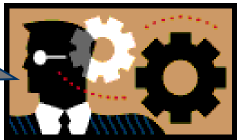



Fuzzy representation




http://blog.peltarion.com/2006/10/25/fuzzy-math-part-1-the-theory/

In fuzzy terms, the height of the man would be classified within a range of [0, 1] as average to a degree of 0.6, and tall to a degree of 0.4.



# Fuzzy Inference Process

- What are the steps involved in creating a Fuzzy Control System?

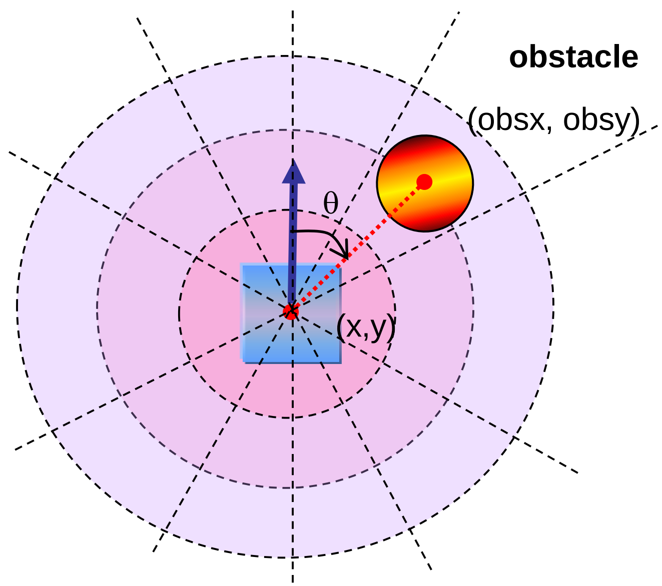
# Fuzzy Inference Process

## Fuzzy Inference Process

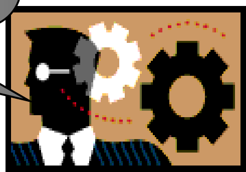

Fuzzification: Translate input into truth values
Rule Evaluation: Compute output truth values
Defuzzification: Transfer truth values into output

# Example 1 : Obstacle Avoidance Problem

## Robot Navigation




Can you describe how the robot should turn based on the position and angle of the obstacle?

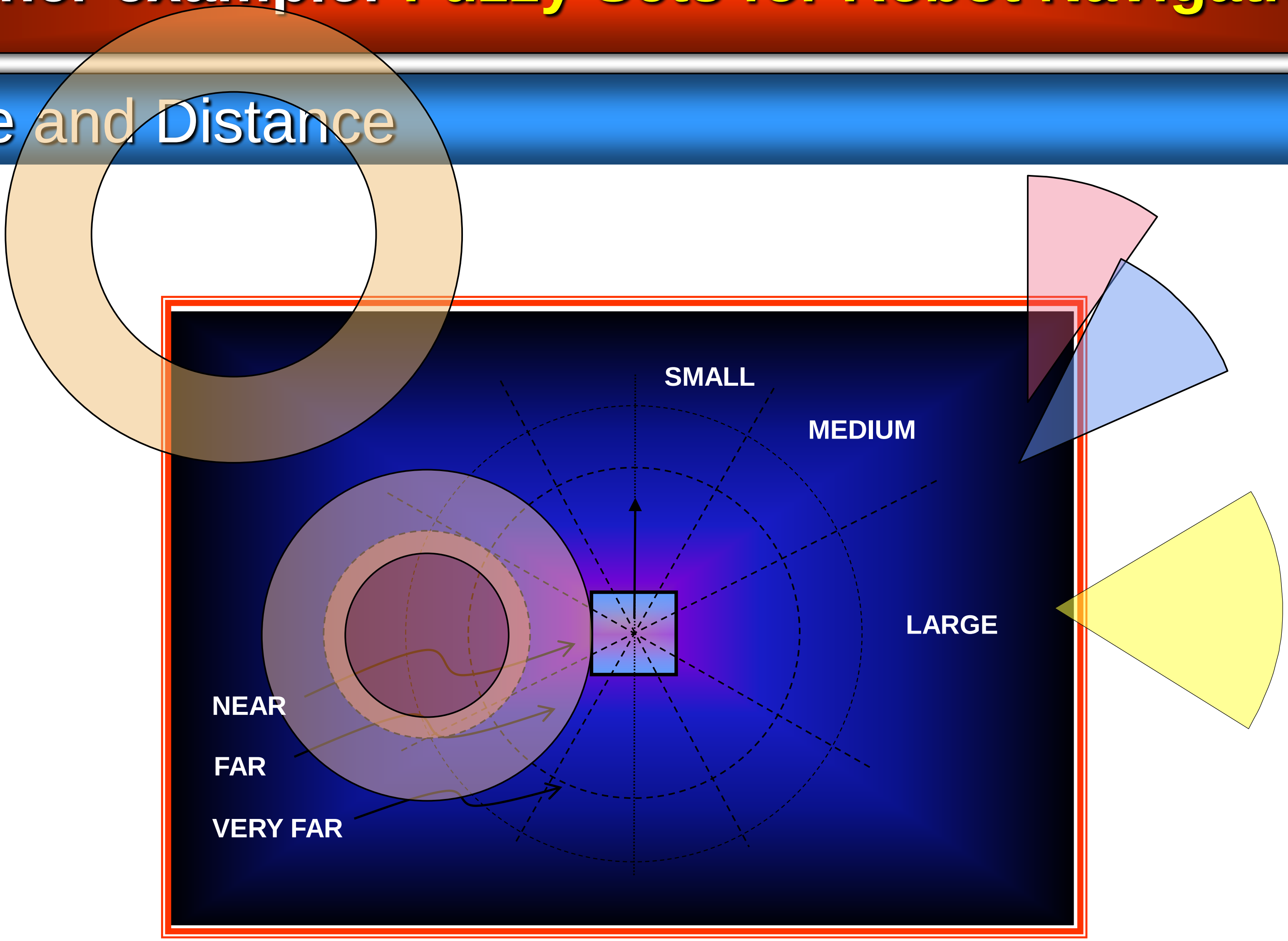


Obstacle Avoidance & Target Pursuit

Demonstration

# Another example: Fuzzy Sets for Robot Navigation

## Angle and Distance




- Sub ranges for angles & distances overlap

# Fuzzy Systems *for* Obstacle Avoidance

Vision System

*Nearest Obstacle (Distance and Angle)*

## Fuzzy System 3 (Steering)

| | *NEAR* | *FAR* | *VERY FAR* |
|---|---|---|---|
| ***SMALL*** | Very Sharp | Sharp Turn | Med Turn |
| ***MEDIUM*** | Sharp Turn | Med Turn | Mild Turn |
| ***LARGE*** | Med Turn | Mild Turn | Zero Turn |

**e.g. If** the *Distance* from the Obstacle is *NEAR* and the *Angle* from the Obstacle is *SMALL* **Then** turn *Very Sharply*.

**Angle**

## Fuzzy System 4 (Speed Adjustment)

| | *NEAR* | *FAR* | *VERY FAR* |
|---|---|---|---|
| ***SMALL*** | Very Slow | Slow Speed | Fast Fast |
| ***MEDIUM*** | Slow Speed | Fast Speed | Very Fast |
| ***LARGE*** | Fast Speed | Very Fast | Top Speed |

*e.g.* **If** the *Distance* from the Obstacle is *NEAR* and the *Angle* from the Obstacle is *SMALL* **Then** move *Very Slowly.*

**Speed**

# Summary of Steps

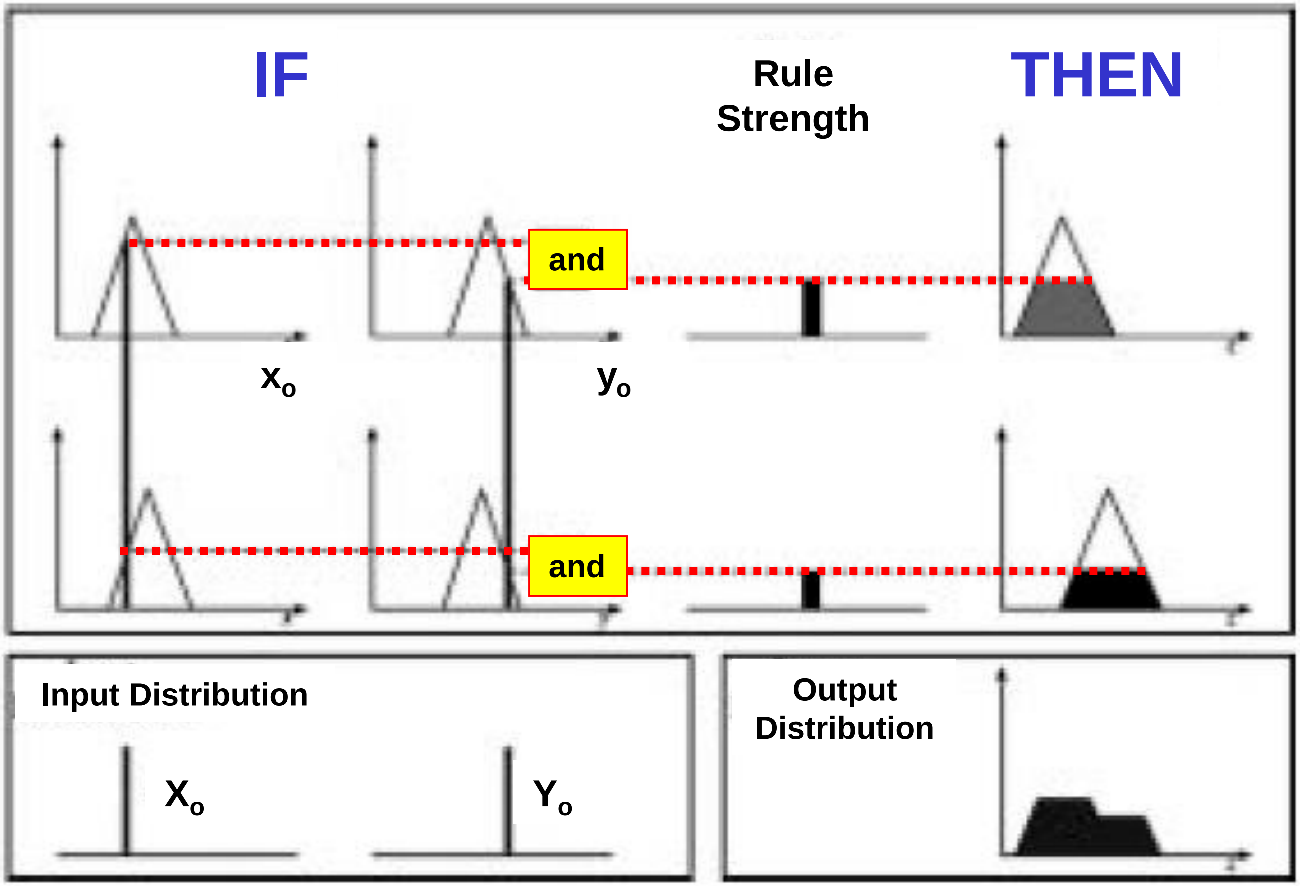
1. determining a set of fuzzy rules
2. fuzzifying the inputs using the input membership functions,
3. combining the fuzzified inputs according to the fuzzy rules to establish a rule strength,
4. finding the consequence of the rule by combining the rule strength and the output membership function (if it's a mamdani FIS),
5. combining the consequences to get an output distribution, and
6. defuzzifying the output distribution (this step applies only if a crisp output (class) is needed).

# Fuzzy Inference

**Fuzzy inference** is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves : Membership Functions, Logical Operations, and If-Then Rules.

# Mamdani Inference System

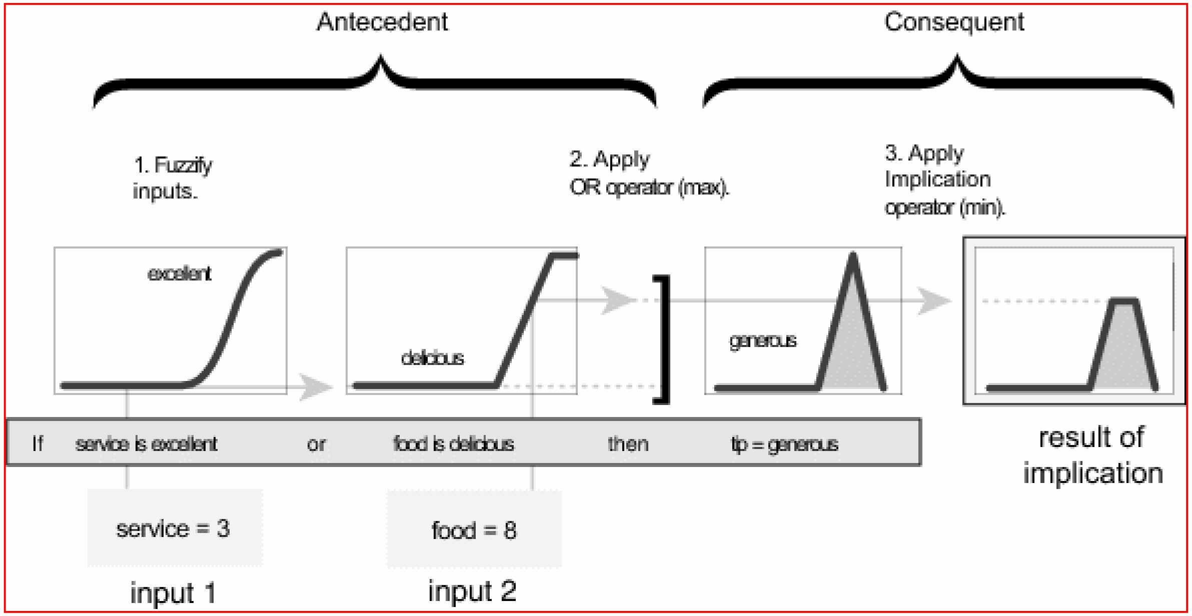
## Two input, two rule Mamdani FIS with crisp inputs




Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output.

# Mamdani FIS

**Mamdani-type inference**, expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification.

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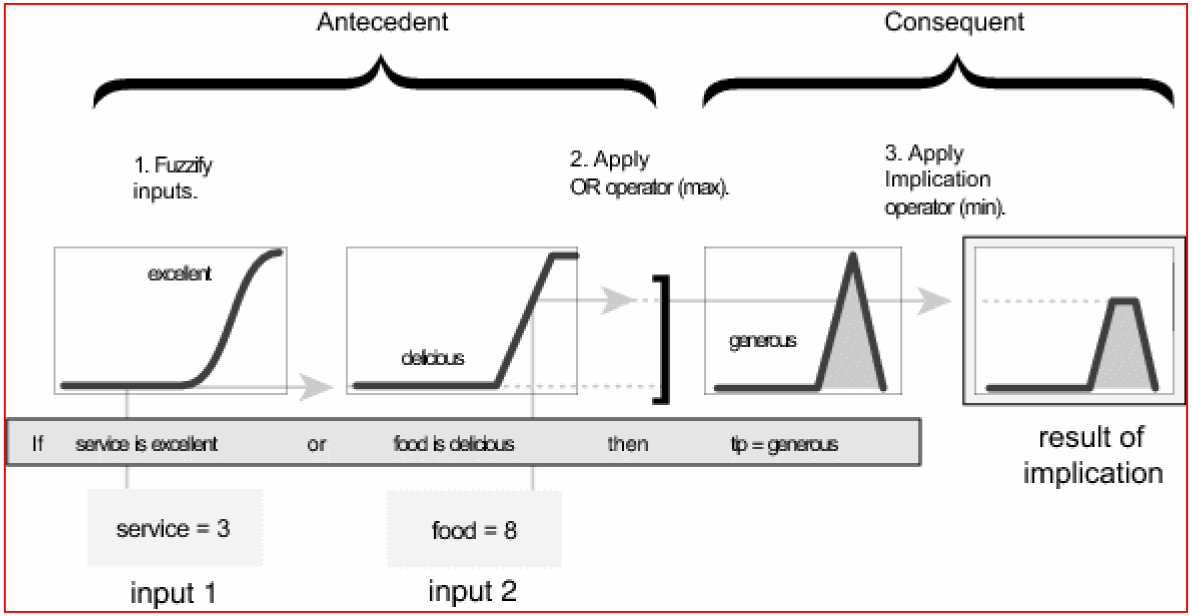


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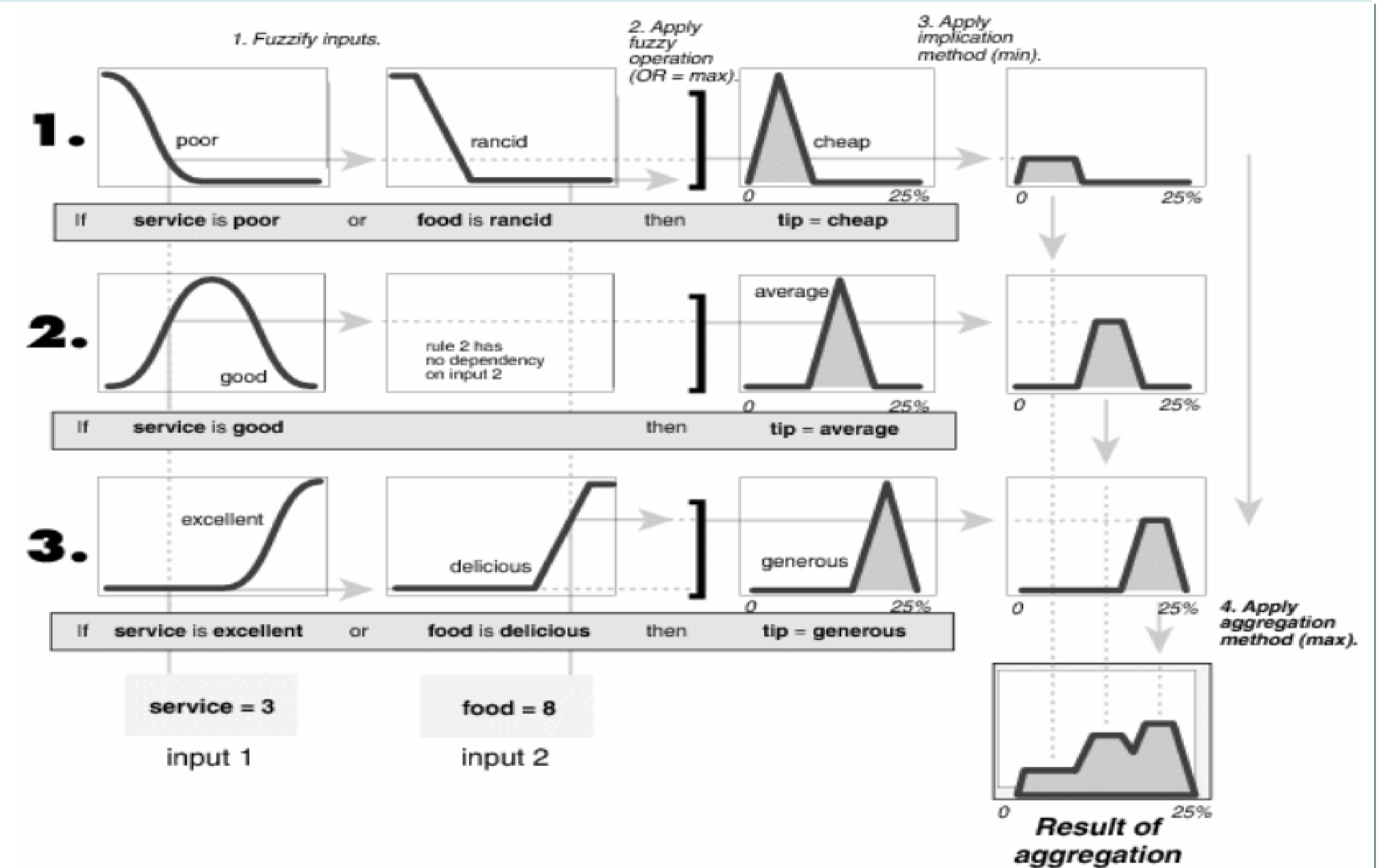
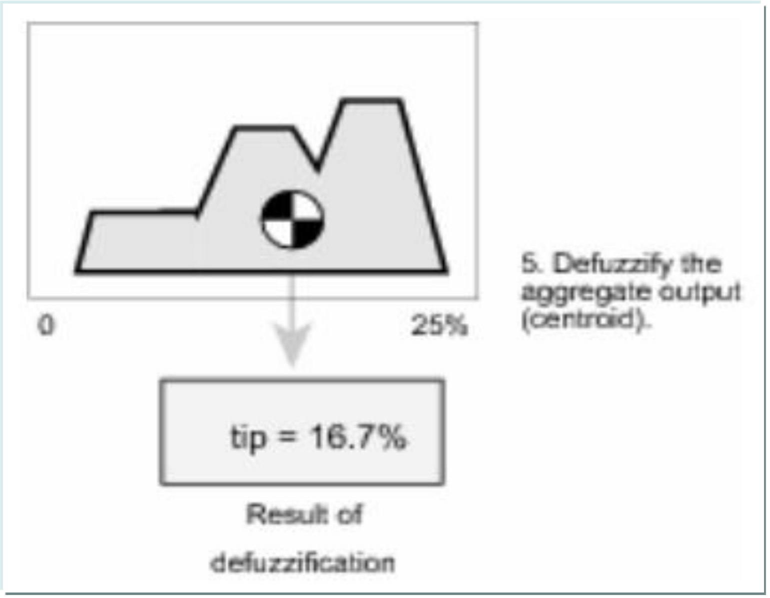
# Mamdani FIS

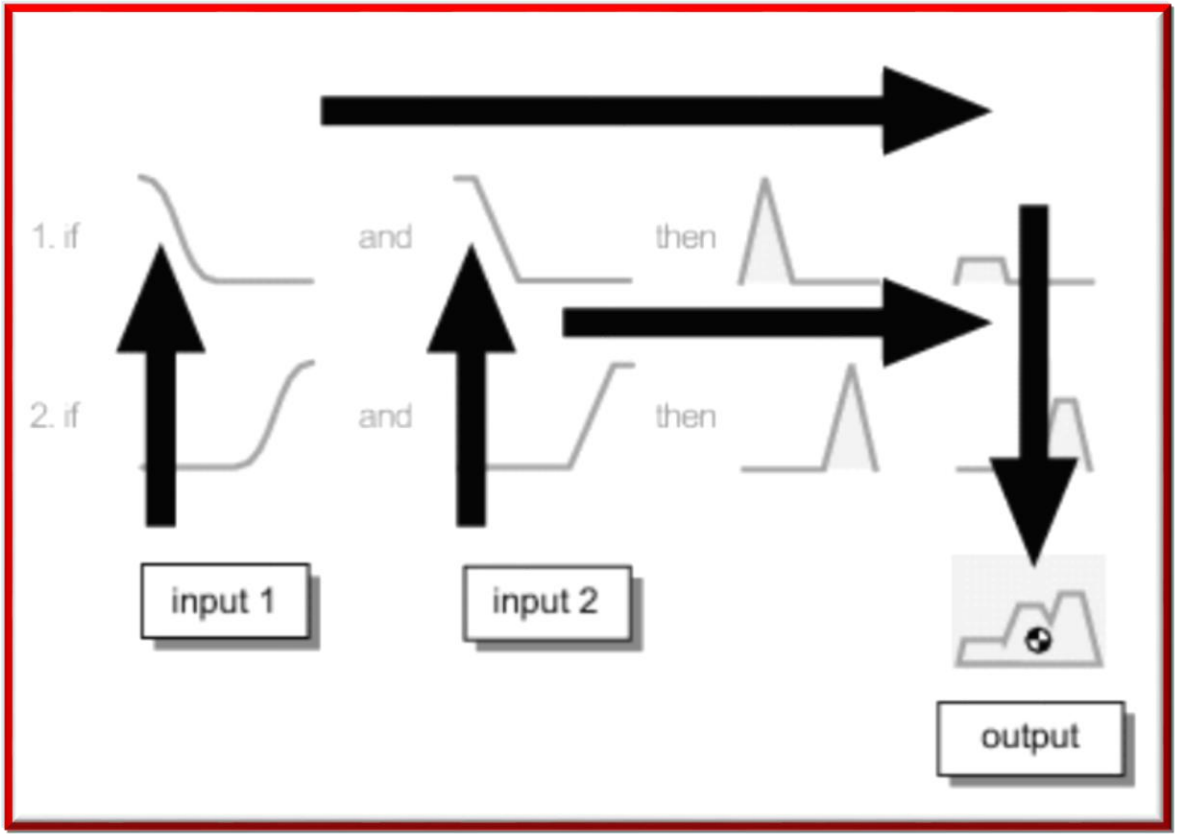


1. Fuzzify inputs.
2. Apply fuzzy operation (OR = max).
3. Apply implication method (min).
1.
poor
rancid
cheap
0
25%
If service is poor or food is rancid then tip = cheap
2.
good
rule 2 has no dependency on input 2
average
If service is good then tip = average
3.
excellent
delicious
generous
If service is excellent or food is delicious then tip = generous
4. Apply aggregation method (max).
service = 3
input 1
food = 8
input 2
Result of aggregation

# Mamdani FIS


0
25%
5. Defuzzify the aggregate output (centroid).
tip = 16.7%
Result of
defuzzification

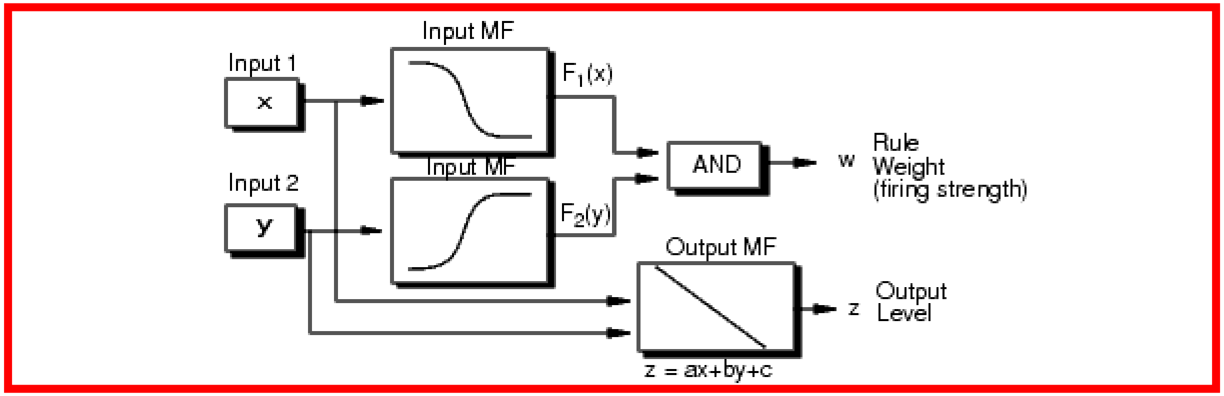
# Flow of Fuzzy Inference




In this figure, the flow proceeds up from the inputs in the lower left, then across each row, or rule, and then down the rule outputs to finish in the lower right. This compact flow shows everything at once, from linguistic variable fuzzification all the way through defuzzification of the aggregate output.

# Sugeno FIS

**Sugeno FIS** is similar to the Mamdani method in many respects. The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant.

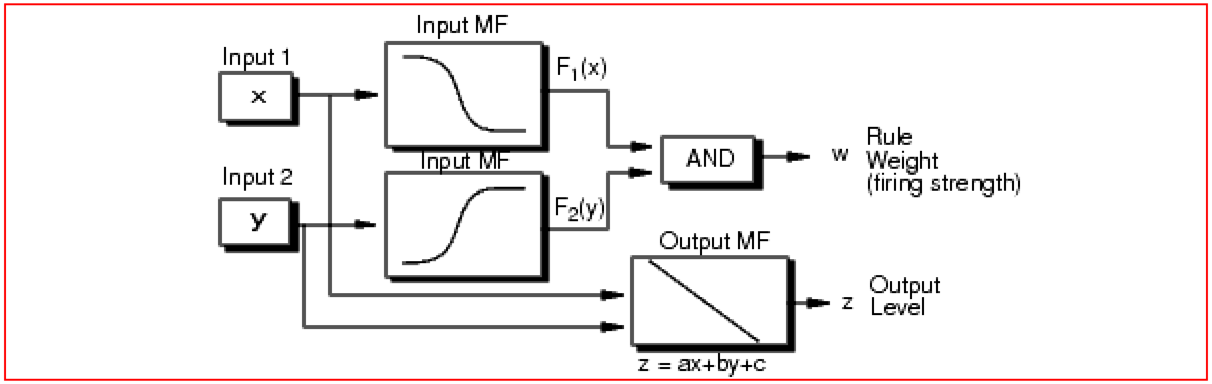


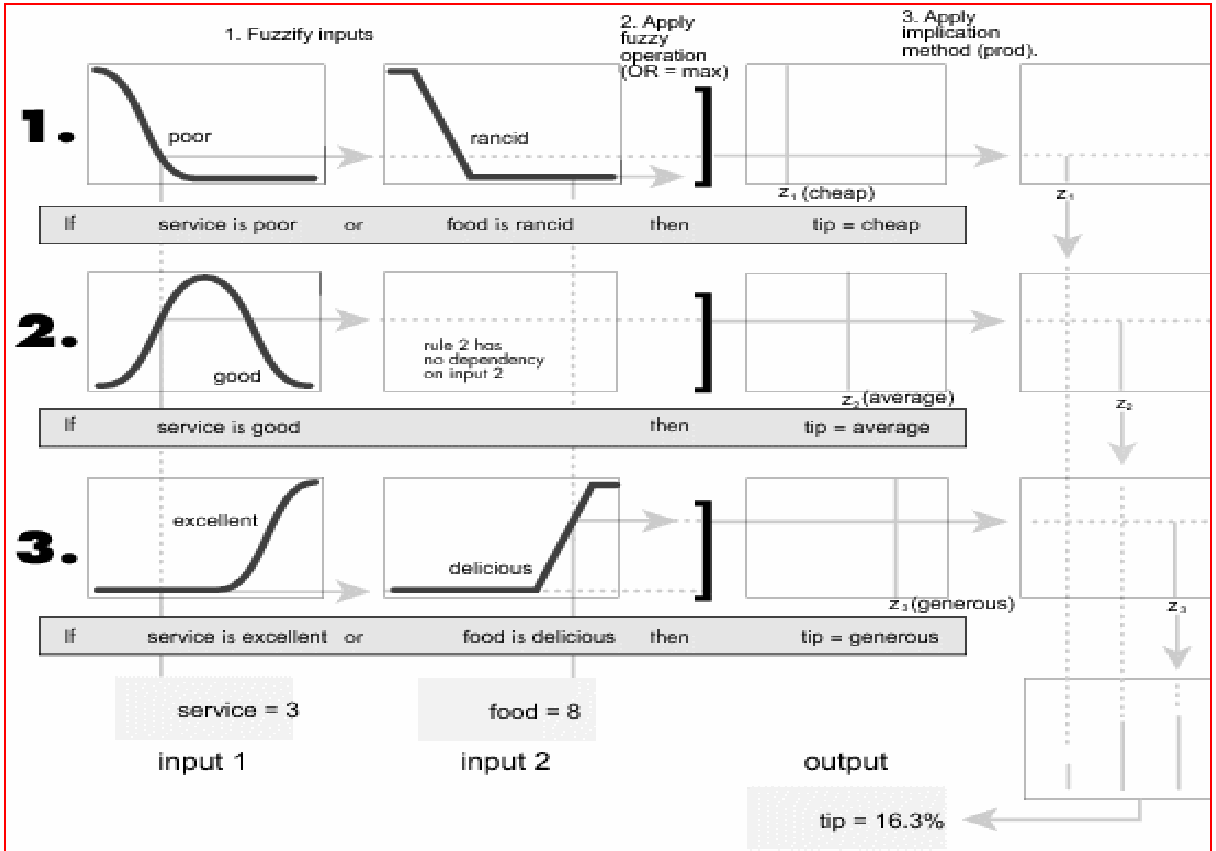

A typical rule in a Sugeno fuzzy model has the form:

If Input 1 = x and Input 2 = y, then Output is **z = ax + by + c**

For a **zero-order Sugeno model**, the output level **z** is a **constant** (a=b =0).

# Sugeno FIS




$$\text{Final Output} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i}$$

# FIS: Sugeno vs. Mamdani

**Advantages of the Sugeno Method**

It is computationally efficient.
It can be used to model any inference system in which the output membership functions are either linear or constant.
It works well with linear techniques (e.g., PID control).
It works well with optimization and adaptive techniques.
It has guaranteed continuity of the output surface.
It is well suited to mathematical analysis.

**Advantages of the Mamdani Method**

It is intuitive.
It has widespread acceptance.
It is well suited to human input.

# Task 2

What is the sequence of steps taken in designing a fuzzy logic controller?

- Following is the sequence for the designing a fuzzy logic machine: Fuzzification->Rule Evaluation->Defuzzification
  when designing a fuzzy logic, we first have to define the fuzzy sets and make appropriate member function. The rule evaluation comes in which matches the sets to its corresponding rules.

# Task 3 : example of control

The objective of this case study is to perform the speed control of a separately excited DC motor (figure 1) using fuzzy logic controller (FLC). The controller will be designed based on the expert knowledge of the system. For the proposed dc motor case, we recommend **7 fuzzy rules** for fuzzy logic controller.

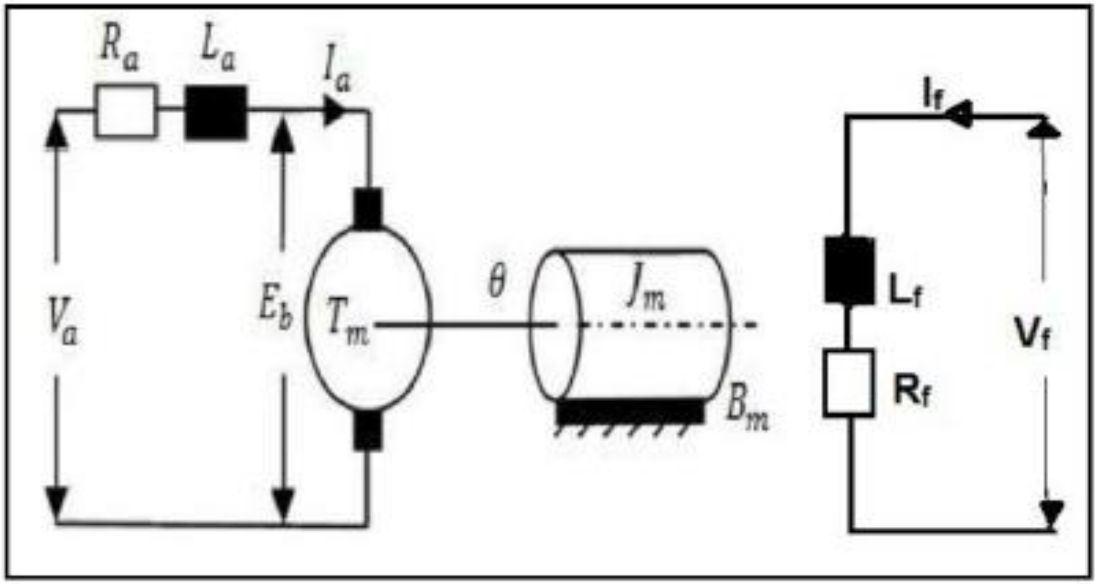



Fig.1 separately excited dc motor model

# Task 3 : example of control

Taking field flux as ∅ and Back EMF Constant as $K_\varphi$.
Equation for back emf of motor will be:

$$E_b = K_\varphi \, \omega$$

Torque:

$$T_m = J_m \left(\frac{d\omega}{dt}\right) + T_L$$

$$T_m = K_\varphi \, I_a$$

$\omega$ is the angular velocity (speed) and friction in rotor of motor is very small (can be neglected) so Bm = 0.
Armature Time Constant:

$$T_a = \frac{L_a}{R_a}$$

# Task 3 : example of control

1) Plot the block diagram of separately excited dc motor based on Laplace transformations of the motor's armature voltage and balance torque.

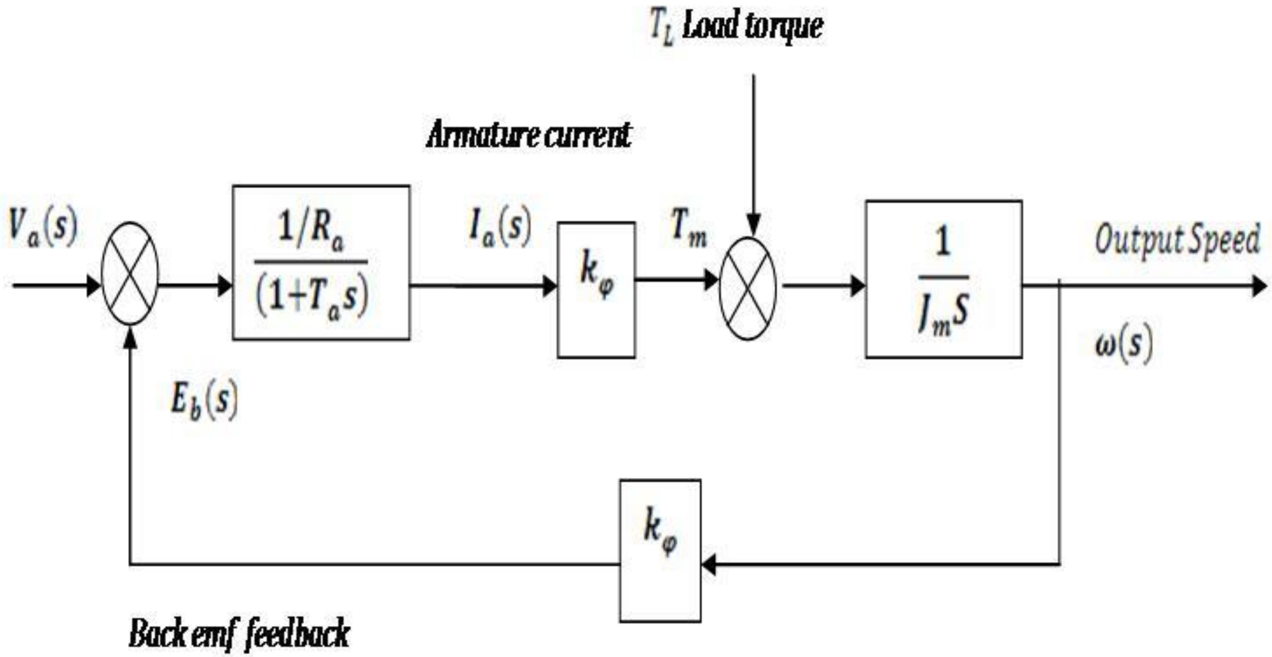



Fig.2 Block diagram of separately excited dc motor

# Task 3 : example of control

2) Define the required fuzzy controller inputs and outputs. Then complete this diagram:

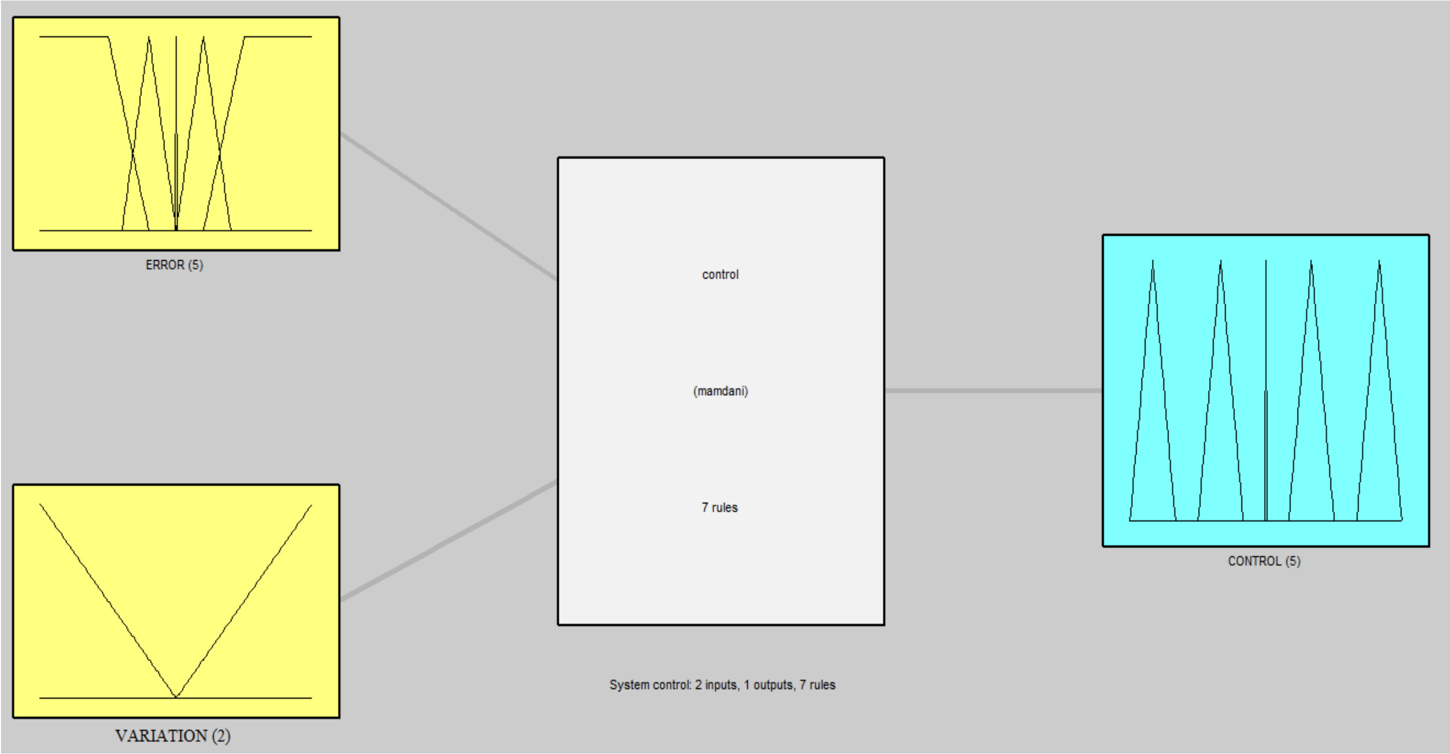



Fig. 3: General structure of the fuzzy controller.

# Task 3 : example of control

3) Deduce the structure of the fuzzy logic controller with closed loop (synopsis of all system with fuzzy controller).

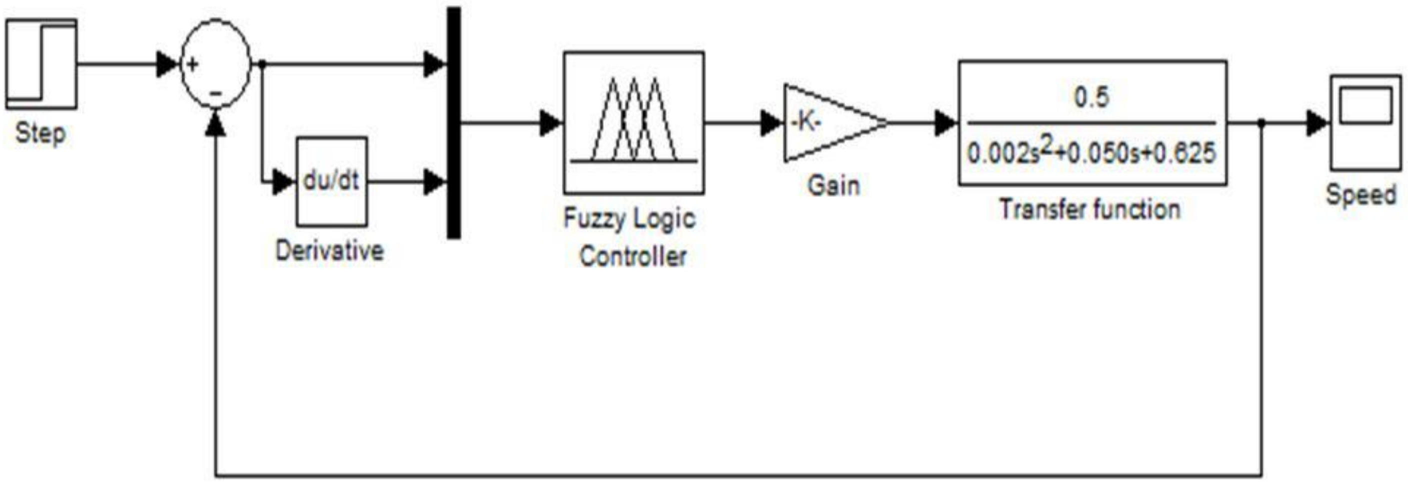



Fig.4 Model of system using fuzzy logic controller

# Task 3 : example of control

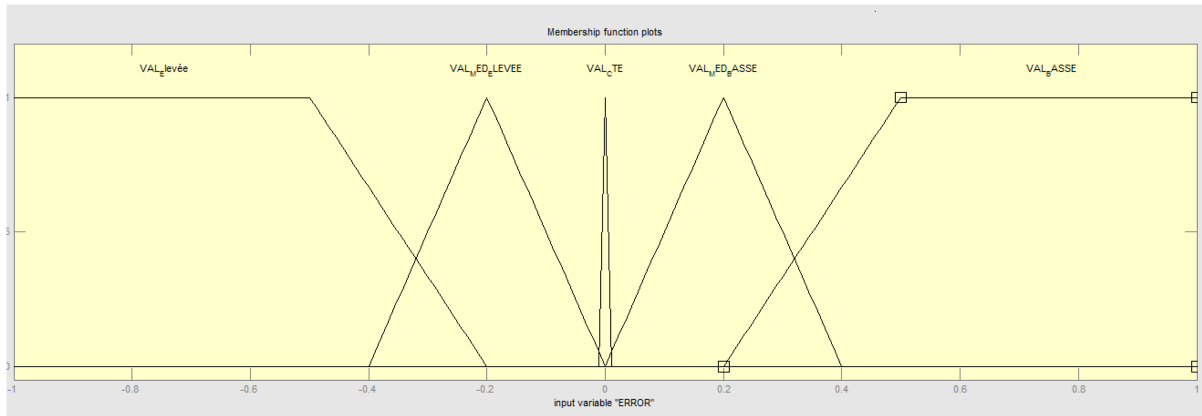
4) Represent membership functions for inputs

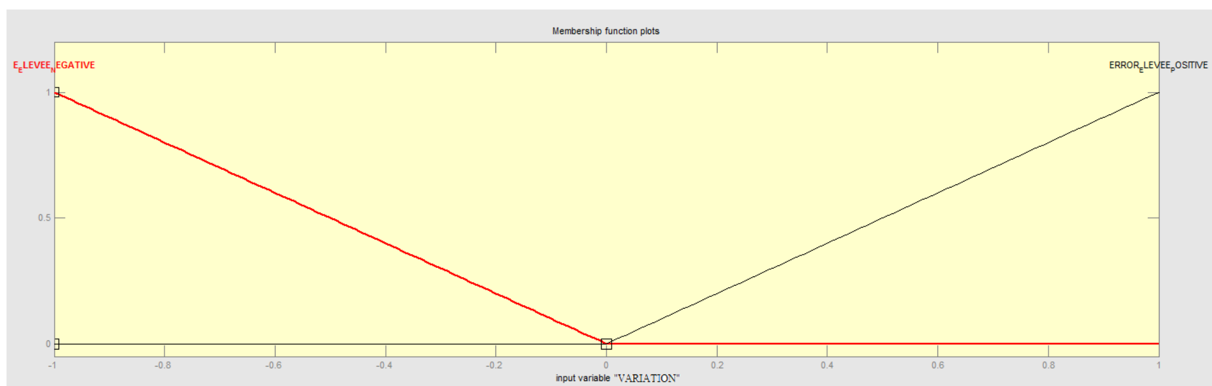
and output variables.

Input 1 range: [-1 1]

Input 2 range: [- 1 1]

Output range: [-30 30].



# Task 3 : example of control

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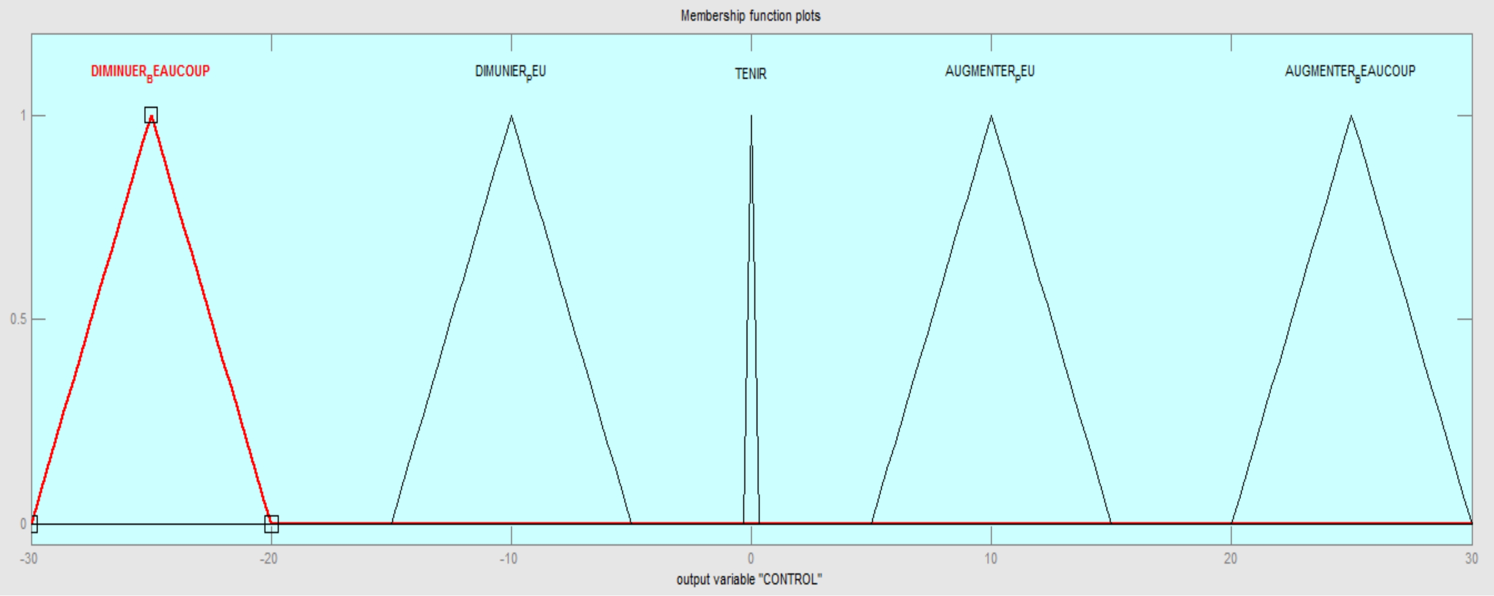


# Task 3 : example of control

5) Enunciate the 7 “if-then” rules necessary for separately excited dc motor speed control.

- If (ERROR is PB) then (CONTROL is AUGMENTER_BEAUCOUP)
- If (ERROR is NB) then (CONTROL is DIMINUER_BEAUCOUP)
- If (ERROR is Z) and (VARIATION is NEGATIVE) then (CONTROL is DIMUNIER_PEU)
- If (ERROR is Z) and (VARIATION is POSITIVE) then (CONTROL is AUGMENTER_PEU)
- If (ERROR is VAL_PM) then (CONTROL is AUGMENTER_PEU)
- If (ERROR is VAL_NM) then (CONTROL is DIMINUER_PEU)
- If (ERROR is Z) then (CONTROL is TENIR)

6) What is the inference system type used here? Is there another type?

MANDANI. YES SUGENO METHOD.

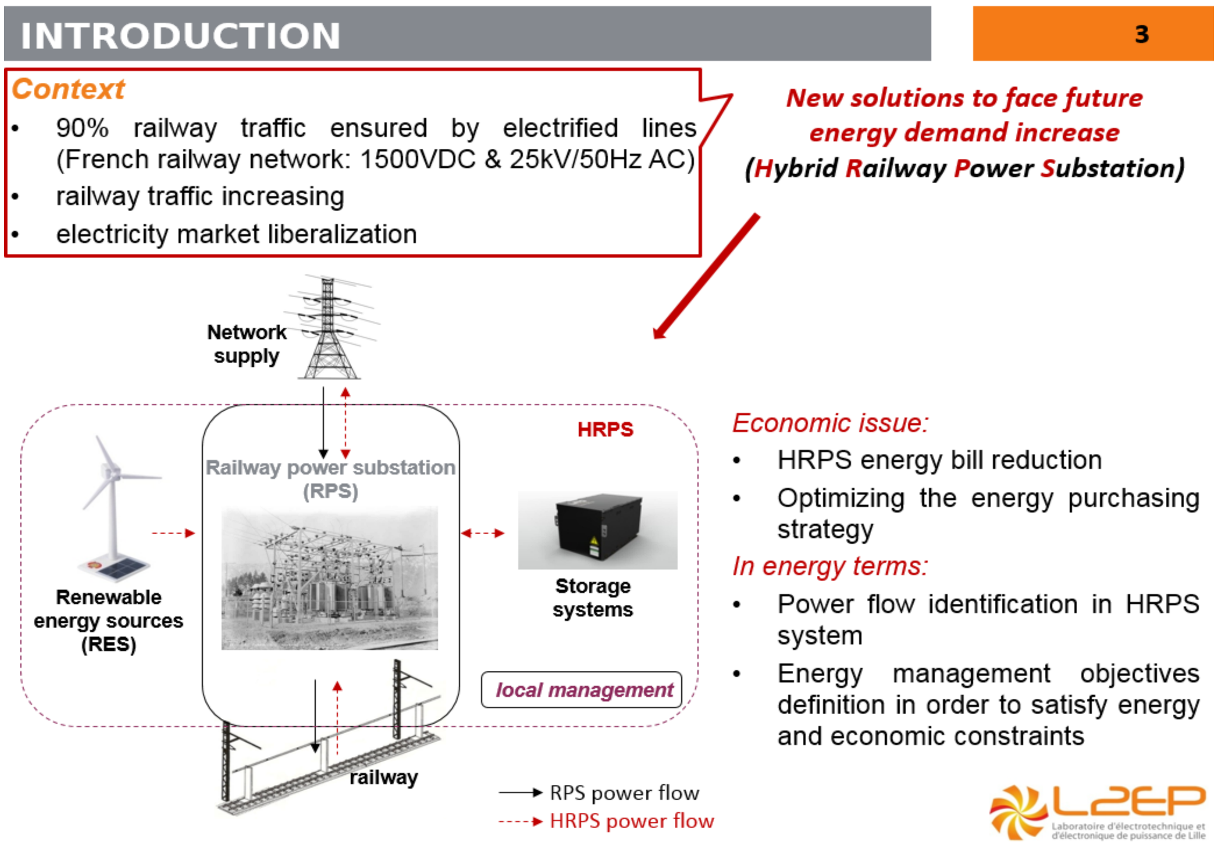
# Task 3 : example of control

7) What is the contribution (benefits) of fuzzy logic in comparison with a conventional PID controller for these case study?

The fuzzy logic approach has minimum overshoot, minimum transient and steady state parameters, which shows more effectiveness and efficiency of FLC than conventional PID controller.

# Task 4 : Fuzzy logic applied to energy management

You are given 3 slides taken from a power point presentation done by a PhD student from HEI L2EP in ELECTRIMACS conference (Spain 2014). **Well understand the problematic and the objectives then respond to the question**.

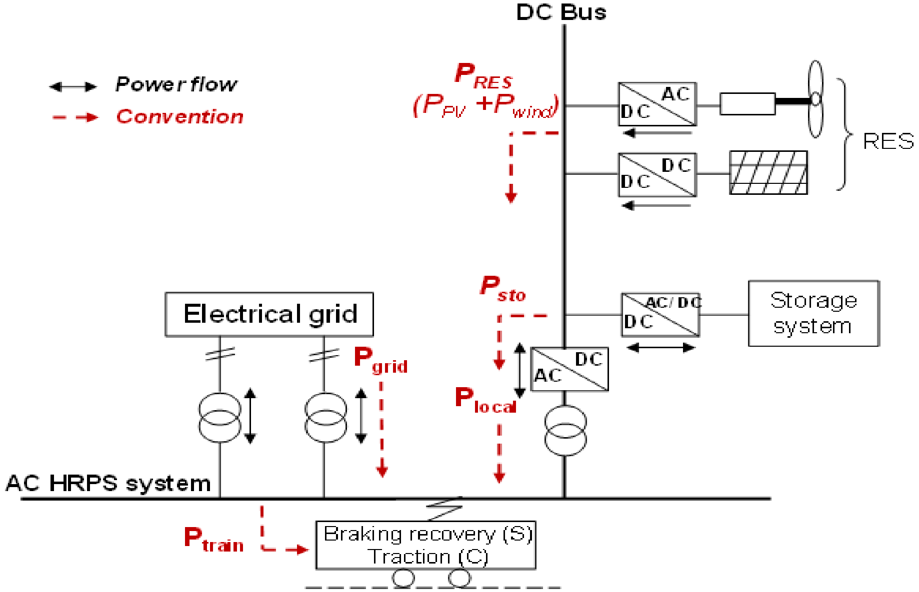


# Task 4 : Fuzzy logic applied to energy management

## SYSTEM DESCRIPTION & SPECIFICATIONS

5

*Hybrid Railway Power Substation architecture*




Hybrid system composed of:
→ photovoltaic (PV) units
→ wind turbines
→ storage systems
→ DC-bus interconnection to the power substation (allowing isolation mode if necessary)

➢ *Power flow balance:*

*RPS:* → $P_{train}=P_{grid}$ $(P_{local}=0)$
*HRPS:* → $P_{train}=P_{grid} + P_{local}$
→ $P_{local}=P_{RES} + P_{sto}$

- *$P_{train}$ is the railway power consumption seen by the HRPS*
- *$P_{grid}$ is the power taken from the grid*
- *$P_{local}$ is the local production (PV, wind, thus $P_{RES}$)*
- *$P_{sto}$ is the storage power*

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

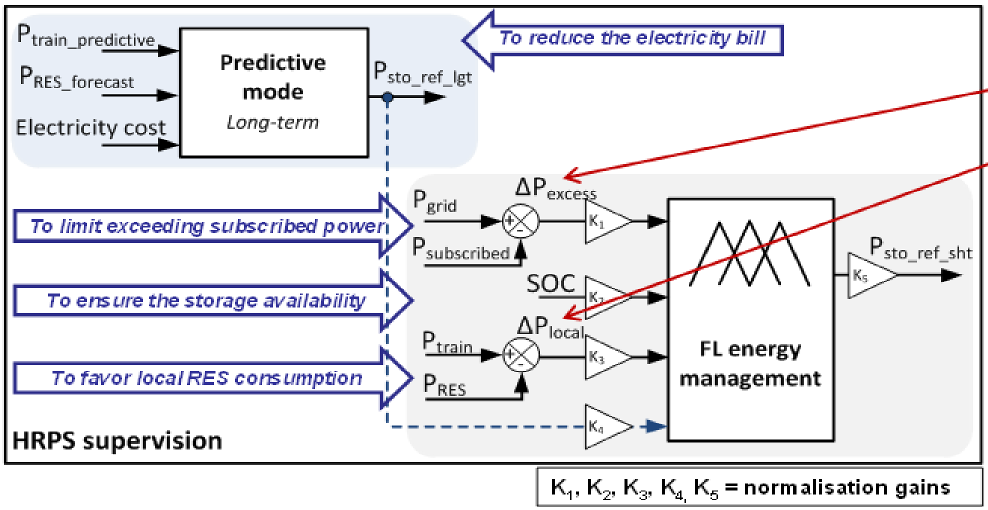
# Task 4 : Fuzzy logic applied to energy management

## DESIGN OF THE SUPERVISION STRATEGY

10

*Methodology for HRPS energy management*

STEP 2
Design of the supervisor




the grid power excess amount

the power difference between train consumption and RES production

# Task 4 : Fuzzy logic applied to energy management

**Question:** Complete this table for work specifications (problem analysis):

| Objectives | Constraints | Means of actions |
|---|---|---|
| *Predictive mode – LONG TERM* | | |
| …………………………………… | …………………………………… | ………………………………. |
| | …………………………………… | |
| | …………………………………… | |
| *Fuzzy Logic energy management – SHORT TERM* | | |
| ……………………………………… | …………………….. | ……………………………….. |
| ……………………………………… | …………………….. | |
| ……………………………………… | …………………….. | |

# Task 4 : Fuzzy logic applied to energy management

| Objectives | Constraints | Means of actions |
|---|---|---|
| **Predictive mode – LONGT TERM** | | |
| Reducing energy bill (regarding short-term trades) | Trains consumption predictions<br>RES forecast<br>Electricity market fluctuations | Storage power ($P_{sto\text{-}ref\text{-}lgt}$) (Predictive reference power) |
| **Fuzzy Logic energy management – SHORT TERM** | | |
| Limitation of subscribed power exceeding<br>Favoring local RES consumption<br>Ensuring storage system availability | Subscribed power<br>Storage limits<br>RES availability | Storage power ($P_{sto\text{-}ref\text{-}sht}$) (Predictive mode adjustment) |

# Task 4 : Fuzzy logic applied to energy management

## DESIGN OF THE SUPERVISION STRATEGY

*Methodology for HRPS energy management*

STEP 1
Work specifications

STEP 2
Design of the supervisor

STEP 3
Chart representation of operating modes
- Functional graphs -

STEP 4
Determination of the membership functions

STEP 5
Chart representation of fuzzy operating modes
- Operational graphs -

STEP 6
Determination of the fuzzy rules

STEP 7
Determination of indicators to measure the achievement of objectives

# Task 4 : Fuzzy logic applied to energy management

## *Methodology for HRPS energy management*

STEP 1

Work specifications

| Objectives | Constraints | Means of actions |
|---|---|---|
| | ***Predictive mode – LONGT TERM*** | |
| Reducing energy bill<br>(regarding short-term trades) | Trains consumption predictions<br>RES forecast<br>Electricity market fluctuations | Storage power ($P_{sto\text{-}ref\text{-}lgt}$)<br>(Predictive reference power) |
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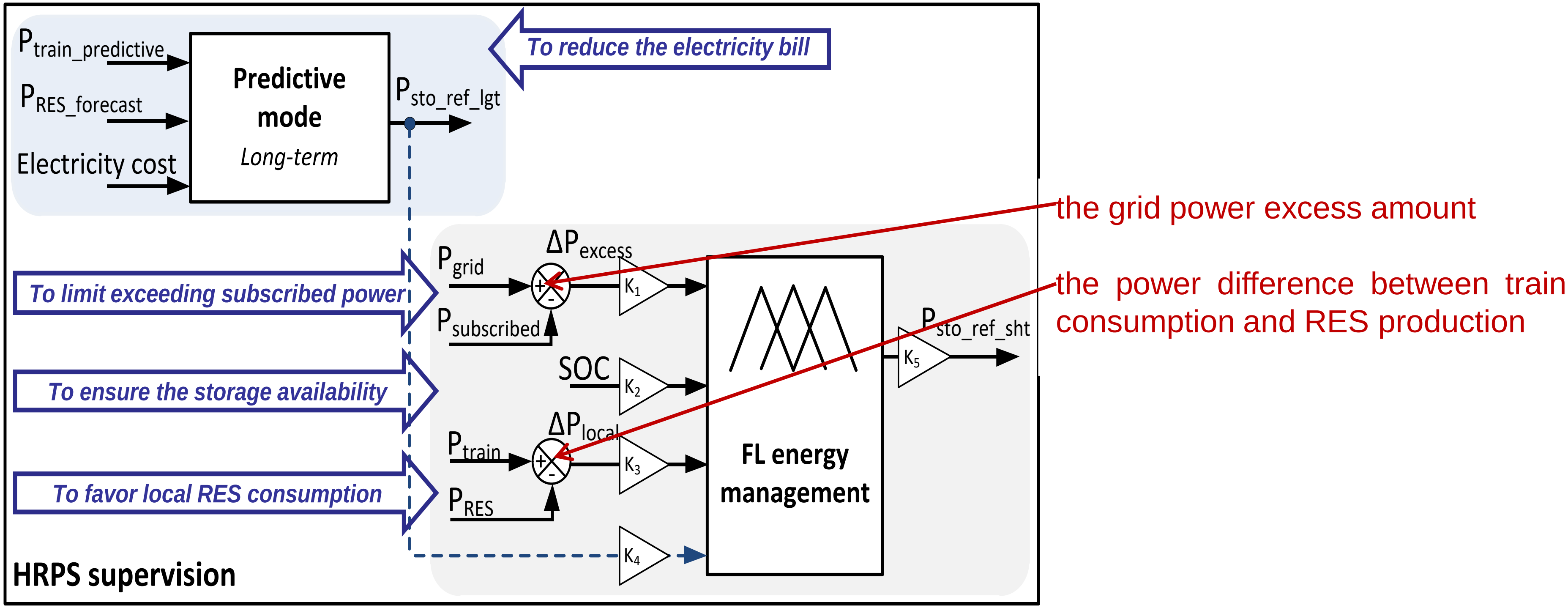
| Limitation of subscribed power exceeding<br>Favoring local RES consumption<br>Ensuring storage system availability | Subscribed power<br>Storage limits<br>RES availability | Storage power ($P_{sto\text{-}ref\text{-}sht}$)<br>(Predictive mode adjustment) |

# Task 4 : Fuzzy logic applied to energy management

## *Methodology for HRPS energy management*

STEP 2

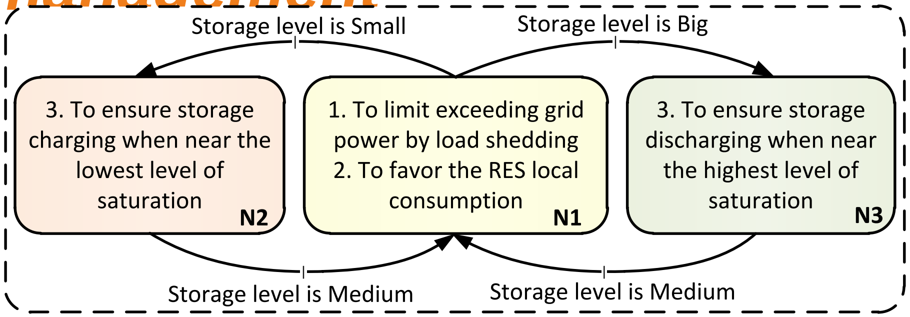
Design of the supervisor




$K_1$, $K_2$, $K_3$, $K_4$, $K_5$ = normalisation gains

# Task 4 : Fuzzy logic applied to energy management

## Methodology for HRPS energy management



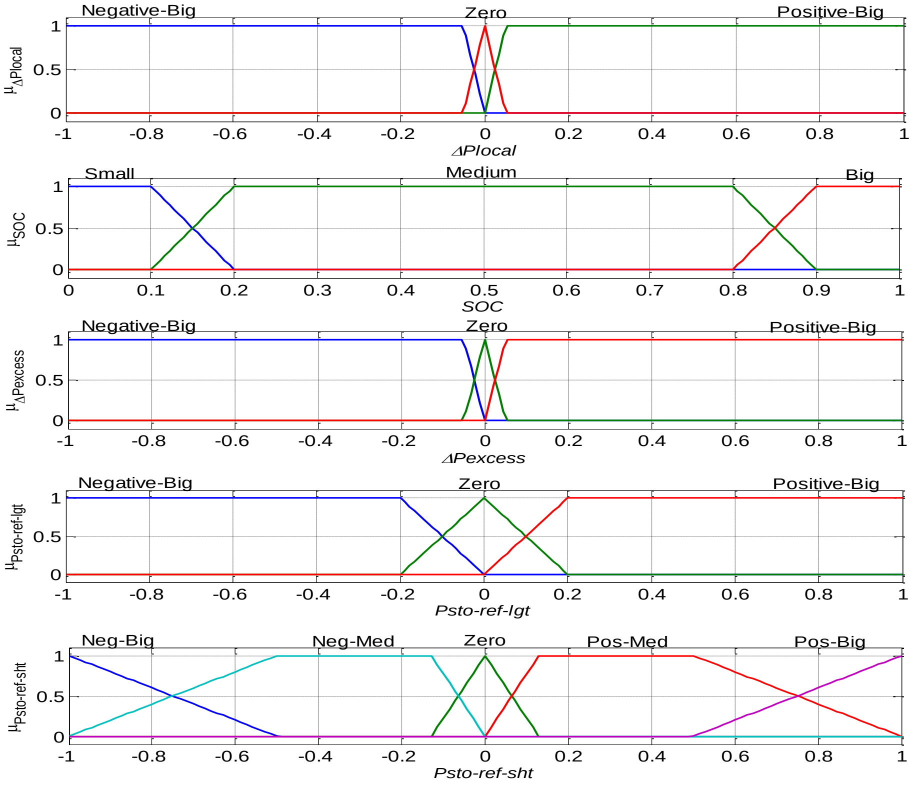

STEP 3

Chart representation of operating modes

- Functional graphs -

STEP 4

Determination of the membership functions




*Inputs:*

- $P_{local}$ (Negative-Big, Zero, Positive-Big)
- SOC (Small, Medium, Big)
- $\Delta P_{excess}$ (Negative-Big, Zero, Positive-Big)
- $P_{sto\text{-}ref\text{-}lgt}$ (Negative-Big, Zero, Positive-Big)

*Output:*

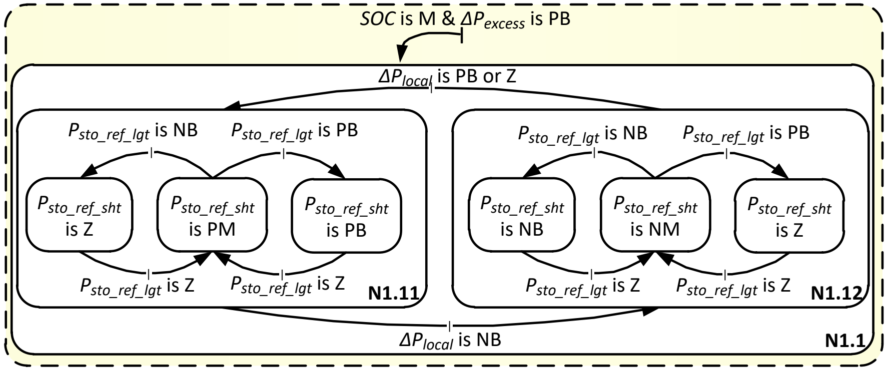
- $P_{sto\text{-}ref\text{-}sht}$ (Negative-Big, Zero, Positive-Big)

# Task 4 : Fuzzy logic applied to energy management

## *Methodology for HRPS energy management*

STEP 5

Chart representation of fuzzy operating modes - Operational graphs -




*from 81 possible cases, only 30 fuzzy necessary rules*

STEP 6

Determination of the fuzzy rules

If $SOC$ is M
and $\Delta P_{excess\_p.u.}$ is NB ($P_{grid} < P_{subscribed}$)
and $\Delta P_{local\_p.u.}$ is PB ($P_{train} > P_{RES}$)
and $P_{sto\text{-}ref\text{-}lgt\_p.u.}$ is NB *(to charge)*
then $P_{sto\text{-}ref\text{-}sht\_p.u.}$ is NB *(charge reference)*

| *Mode* | *Inputs* | | | | *Output* |
|---|---|---|---|---|---|
| | SOC | $\Delta P_{local}$ | $\Delta P_{excess}$ | $P_{sto\text{-}ref\text{-}lgt}$ | $P_{sto\text{-}ref\text{-}sht}$ |
| *N1.11* | M | not NB | PB | PB | Z |
| | M | not NB | PB | Z | PB |
| | M | not NB | PB | PB | PB |
| *N1.12* | M | NB | PB | NB | NB |
| | M | NB | PB | Z | NM |
| | M | NB | PB | PB | Z |
| | | | … | | |

# Task 4 : Fuzzy logic applied to energy management

## *Methodology for HRPS energy management*

STEP 7

Determination of indicators to measure the achievement of objectives

*Economic indicator* (monthly component of the exceeding subscribed power)

$$CMDPS = \sum_{t \in T} \alpha \cdot k_t \sqrt{\sum_{x \in X_t} \Delta P_{excess}^2(x)}$$

$$\Delta P_{excess} = P_{grid} - P_{subscribed}$$

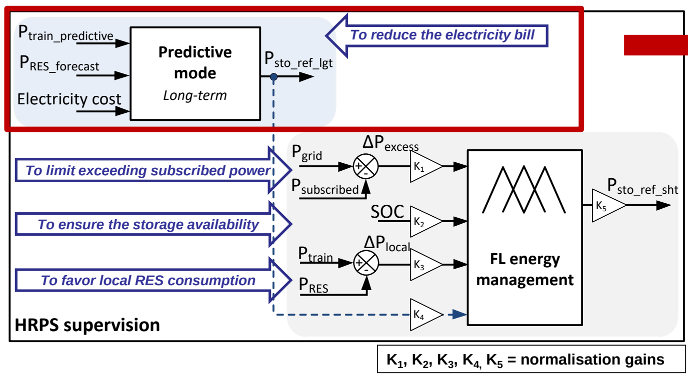
- five tariff time periods *T*
- *α=0.3584€/kW*
- $k_t$ (%) is a power coefficient for each time tariff period *t*
- $X_t$ represents the index set *x* belonging to each time class *t*).

*Energy indicator* (ratio between the locally consumed energy of RES and the produced one)

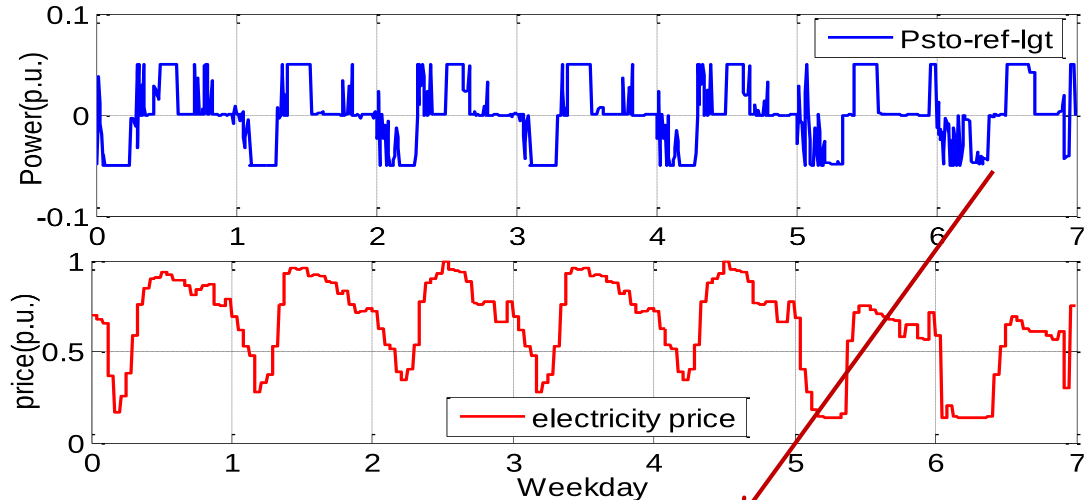
$$I_{RES}(\%) = \frac{E_{RES} - E_{RES\_noncons}}{E_{RES}} \cdot 100$$

# Task 4 : Fuzzy logic applied to energy management

## Predictive mode storage reference power



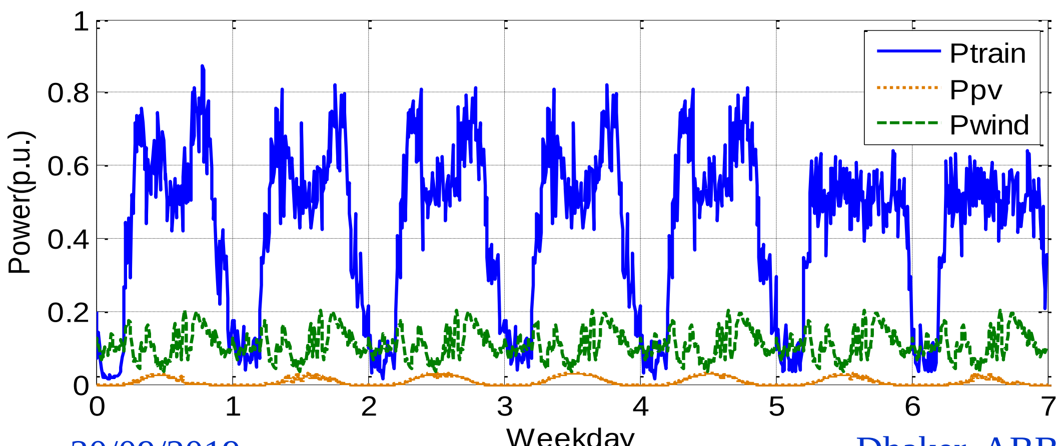

*Depends on electricity price in short term trades*




*Storage system:*

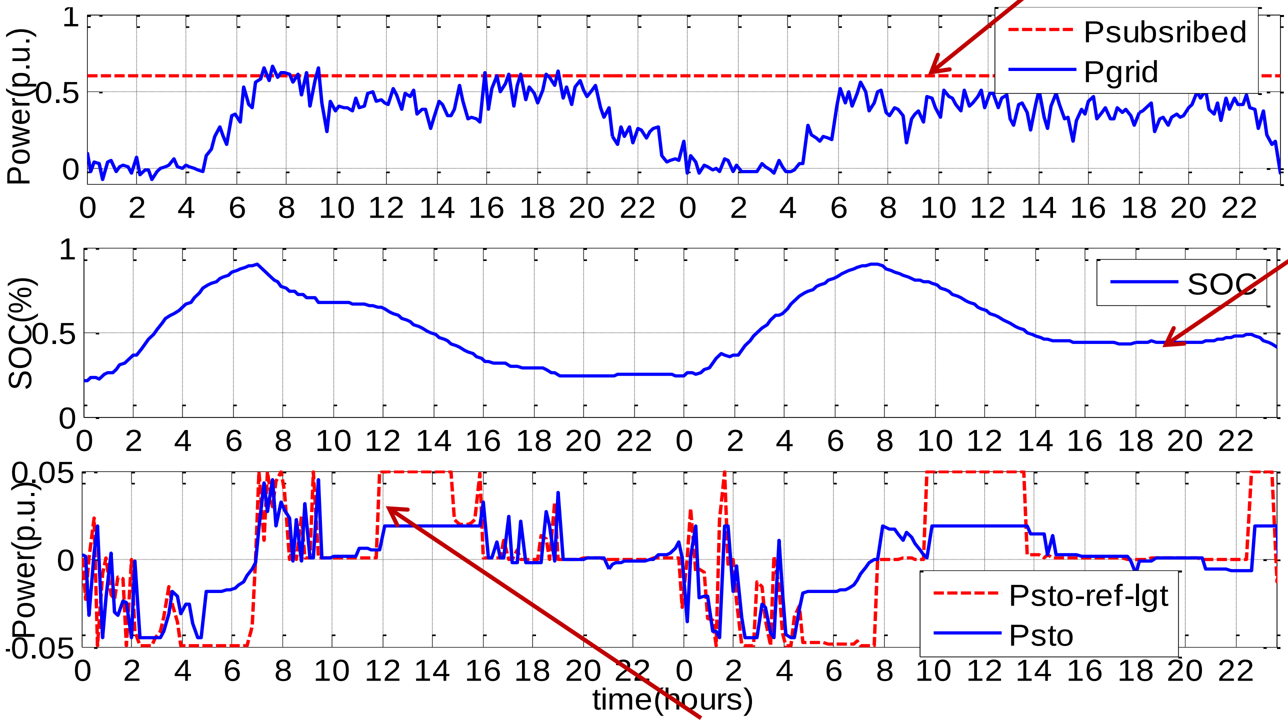
- $C_{sto}$ = 5000 kWh
- $P_{sto\text{-}max}$ = 1MW
- $\eta_{charge}$=90%, $\eta_{discharge}$=90%
- $SOC_{min}$, $SOC_{max}$
- time response constant *(τ=0.5s)*

## Production and consumption profiles



# Task 4 : Fuzzy logic applied to energy management

## *Case 3: storage power adjustment*




the subscribed power is reduced thanks to RES local consumption and storage management

storage system charges when RES exceed train consumption and when economic interesting

adjustment of $P_{sto\text{-}ref\text{-}lgt}$ reference power

# Task 4 : Fuzzy logic applied to energy management

## *Comparison of different supervision cases*

Subscribed power is reduced five times in HRPS supervision

| ***Study case*** | ***CMDPS*** | ***$I_{RES}$*** |
| --- | --- | --- |
| Reference case | 5338 € | 0% |
| Case 1 (Predictive mode) | 1024 € | 96,5% |
| Case 2 (FLEM strategy) | 1036 € | 95,5% |
| Case 3 (Adjustment) | 942 € | 96,9% |

well performance of FLEM strategy compared to predictive mode results

RES is locally consumed almost in totality

# References

This first theoric part is extracted from : Fuzzy logic Massey University course.
http://www.massey.ac.nz/~nhreyes/MASSEY/159741/Lectures/Lec2012-3-159741-FuzzyLogic-v.2.pdf

Petronela Pankovits; **Dhaker Abbes**; Christophe Saudemont; Othman Moumniabdou; Julien Pouget; Benoit Robyns, « Energy Management Multi-Criteria Design for Hybrid Railway Power Substations, », 11th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems (ELECTRIMACS 2014).

Umesh Kumar Bansal and Rakesh Narvey, «Speed Control of DC Motor Using Fuzzy PID Controller », Advance in Electronic and Electric Engineering. ISSN 2231-1297, Volume 3, Number 9 (2013), pp. 1209-1220 , © Research India Publications.

Thank you for your attention !