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Protection System for Induction Motor based on Sugeno Inference

***Abstract**. The induction motor is a most important drive in the production area. These motors are used in various industrial applications. They can be protected from the different mechanical and electrical faults using different protection systems. The protection is very important to detect abnormal motor running conditions such as over current, over voltage, overload, over temperature, and unbalance conditions. In the classical protection systems, the time delay is adjusted constantly without considering the fault level. This paper presents protection system for induction motor based on Sugeno Inference. The time delay is computed by this intelligent protection for different faults. The obtained results are interesting and show the interest of the proposed intelligent protection.*

Streszczenie. W artykule zaprezentowano system zabezpieczeń silnika indukcyjnego bazujący na Sugeno Inference. Określano opóźnienie czasowe dla różnych rodzajów błędów. W stosunku do istniejących systemów proponowany system umożliwia bardziej precyzyjne określenie błędów. ***Zabezpieczenie silnika indukcyjnego przy wykorzystaniu systemu Sugeno Inference***

Keywords: Induction motor protection, Fuzzy logic, Sugeno inference– Overvoltage, Over current, Time delay
Słowa kluczowe: silnik indukcyjny, detekcja błędów silnika, Sugeno Inference.

Introduction

The induction motor is a most central drive in the modern era of automation. These motors are used in various industrial applications. But they can be protected from the different mechanical and electrical faults for helping their purposes. The induction motor experiences various kinds of electrical faults such as over voltage or under voltage, unbalanced voltage, overload, earth fault, phase reversing and single phasing. Due to these faults, the windings in the motor gets heated which lead to reduce the life of the motor. The faults in motor may occur due to faults in the motor or in the driven plant. The investigation of faults of induction motors focus on monitoring of thermal, vibration, electrical, noise, torque, and flux so far. The electricity-related faults are one of the important problems that demands special attention. Various sensors are used to detect the distinctive signals resulting from these faults. To extract the particular features from the faults, different types of signal processing techniques are applied to these sensor signals [1]. Nowadays, microcontroller-based methods can monitor the operating induction motor continuously that does not require human inspection to detect faults in motor. There has been extensive research on detecting abnormal conditions of induction machine using microcontroller-based systems [2–6].

Sugeno inference for protection system

The protection system is to detect the failures in a rapid manner that occurs in the system. The intelligent protection is expected to perform the protection functions against the following conditions:

A- Over voltage: It is a condition in which voltage is higher than the rated level that is most often used to refer to voltage values in power lines. The problem can affect electric and electronics devices in all industries connected to the power line.

B- Over current: It is a condition in which current is higher than the rated current capacity that can be caused by a short circuit, loose connection, and ground fault.

C- Winding temperature is one of the most important parameters in induction motors since every rise in temperature greatly reduces the expected life span. The heat occurs in the winding of the motors if they operate for a long time.

D-Voltage unbalance occurs in a three-phase system where the magnitudes of phase or line voltages are different and the phase angles differ from the balanced conditions, or voltage unbalance generally causes torque, speed variations, additional losses, current unbalance, and noise in three-phase motors.

E- Current unbalance leads to higher losses, circulating currents in windings, and increased heat in the motor. The current unbalance stems from voltage unbalance, large and unequal distribution of phase loads, and the circulating currents in windings can cause bearing failures.

F- Low voltage could occur when a motor is suddenly connected to a power supply and voltage falls to a level too low for safe operation of motor. The under voltage increases the motor current, the rated copper losses, and temperature of windings [7]. The term fuzzy means things which are not very clear or vague [8]. In real life, we may come across a situation where we cannot decide whether the statement is true or false. At that time, fuzzy logic offers very precious flexibility for reasoning. We can also consider the uncertainties of any situation. Fuzzy logic algorithm helps to solve a problem after considering all available data. Then it takes the best possible decision for the given the input. The fuzzy logic method imitates the way of decision making in a human which consider all the possibilities between digital values true and false. Fuzzy systems are robust because the system has been designed to control within some frame of uncertain conditions. Outputs of the system are used in formulating the system structure itself. Conventional systems analyze requires a model based on a collective set of assumptions needed to formulate a mathematical form. Since most industrial applications currently are more complex, fuzzy control should be developed about the control process exists by using a number of fuzzy rules. In this study, the proposed intelligent system for the induction motor protection systems was developed. In this intelligent protection, the time delay calculation used to stop motor was derived with fuzzy rules based on Sugeno inference. These values were determined according to characteristics of the chosen motor.

Sugeno inference

Sugeno inference 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[9-10].

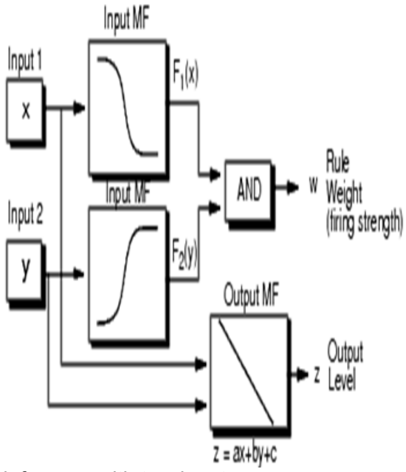

Fig. 1. Sugeno inference with two inputs

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 inference, the output level z is a constant (a=b =0).
The final output is computed by the equation below:

$$\text{(1)} \qquad Final \text{ Output} = \frac{\sum_{i=1}^{N} \mathrm{w}_i z_i}{\sum_{i=1}^{N} w_i}$$

Defuzzification

Defuzzification function converts the conclusions reached by the inference mechanism into the inputs to the plant. In the Sugeno inference, the defuzzification is implemented by two methods: the weighted average (Wtaver) and the weighted sum (Wtsum) which are represented by the equations below:

A-Weighted average (Wtaver)

$$x^* = \frac{\sum_{i=1}^{n} \mu_{Ci}(x_i)x_i}{\sum_{i=1}^{n} \mu_{Ci}(x_i)} \qquad (2)$$

B-Weighted sum (Wtsum)

$$x^* = \sum_{i=1}^{n} \mu_{Ci}(x_i)x_i \qquad (3)$$

where, C1, C2, ...Cn are the output fuzzy sets and (xi) is the input values. In this work, the weighted average is used to complete the defuzzification method.

Simulation and discussion

The induction motor which is used in this work has the characteristics presented on table 1.

Table 1. Induction motor caracteristics

Puissance (kW)	4.0	Vitesse (tr/min)	1430
Tension (V)	220/380	Couple (Nm)	12.73
Current (A)	7.14	Rendement (%)	84

The nominal phase current is 7.14 A, and the nominal power is 4.0 kW. The maximum permissible voltage unbalance and current unbalance are ±10%. The permissible under voltage is 200 V.

The maximum winding temperature in nominal operating mode is 140 °C. The limit values of the linguistic variables are depicted on table 2.

Table 2. limit values of input output variables

	Min	Max
Overvoltage (V)	240	>270
Over current (A)	7.14	>10.5
Temperature (°C)	135	>155
Voltage unbalance (V)	22	>50
Current unbalance (A)	0.714	>2
Low voltage (V)	200	<160
Time delay (s)	0	3.5

The simulation of the induction motor protection system based on the Sugeno inference shown in the figure below is composed of two fuzzy controllers. The first fuzzy controller controls the input linguistic variables: Overvoltage, over current, and temperature. The second fuzzy controller controls the input linguistic variables: Voltage, current imbalance, and low voltage. Both controllers have the same output which represents the output.
The rule bases of the two controllers are presented on the table below:

Table 3. Rule Base samples for the first fuzzy controller

Overvoltage	Over current	Temperature	Output
OVL	OCL	TL	VL
OVL	OCL	TM	VL
OVL	OCM	TH	N
OVL	OCH	TL	LN
OVM	OCH	TH	VS
OVH	OCL	TL	LN
OVL	OCM	TL	LN
OVL	OCL	TL	VL
NA	OCL	TL	VL

where,
OVL, Overvoltage Low, OVM, Overvoltage Medium, OVH, Overvoltage High
OCL, Over current Low, Over current Medium, Over current High
TL, Temperature Low, TM, Temperature Medium, TH, temperature High
VL, Very long, N, normal, LN: long, VS, Very short

Table 4. Rule Base samples for the second fuzzy controller

Voltage unbalance	Current unbalance	Low voltage	Output
VUL	CUL	LVL	VL
VUL	CUL	LVM	VL
VUL	CUL	LVH	LN
VUL	CUM	LVL	VL
VUL	CUM	LVM	LN
VUL	CUM	LVH	N
VUL	CUH	LVL	LN
VUM	CUM	NA	N

where,
VUL, Voltage Unbalance Low, VUM, Voltage Unbalance Medium, VUH, Voltage Unbalance High
CUL, Current Unbalance Low, CUM, Current Unbalance Medium, CUH, Current Unbalance High
LVL, Low Voltage Low, LVM, Low Voltage Medium, LVH, Low Voltage High
The output membership function values of the both controllers are below:

Table 5. The output membership function values

VS	S	N	LN	VL
0.15	1.1	1.8	2.3	3.1

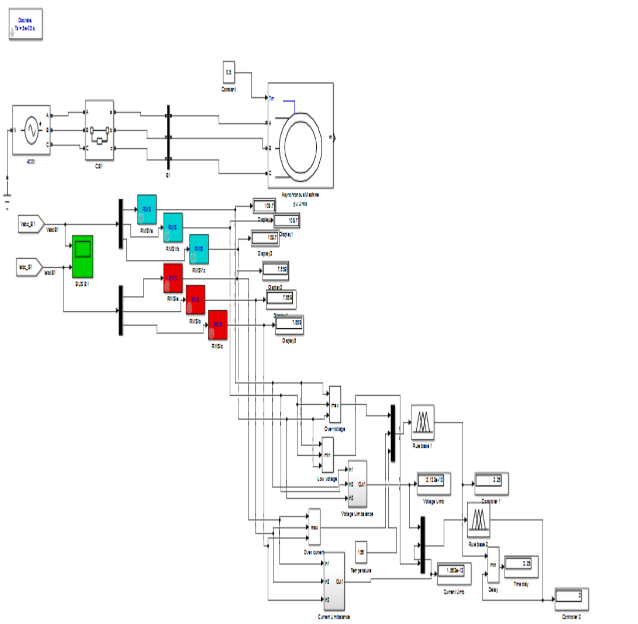

Fig. 2. Simulation of the protection system for induction motor based on Sugeno Inference

The fuzzy inference system functions of the two controllers are built on Matlab fuzzy logic designer as is shown on the figures below:

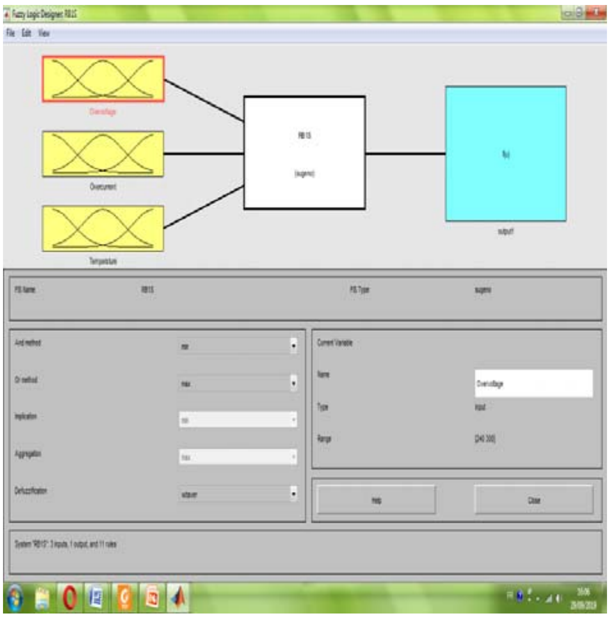

Fig. 3. Fuzzy logic designer for the first fuzzy controller

Both controllers are the same fuzzy inference properties which are presented below:

And method = min

Or method = max

Defuzzification = wtaver

The simulation results of the first controller are presented on the table below:

The figure 5 shows the outputs of the test N° 2.

Table 6. First controller's results

N° test	Overvoltage (V)	Over current (A)	Temperature (°C)	Output1 (s)
1	256.6	7.8	144.5	2.82
2	260.9	8.8	157.2	1.5
3	270.9	9.6	155.5	3
4	241.2	7.3	138.3	2.9
5	246.3	8.1	144.1	2.6
6	249.9	9.3	158.3	2.22
7	240	7.14	135	2.9

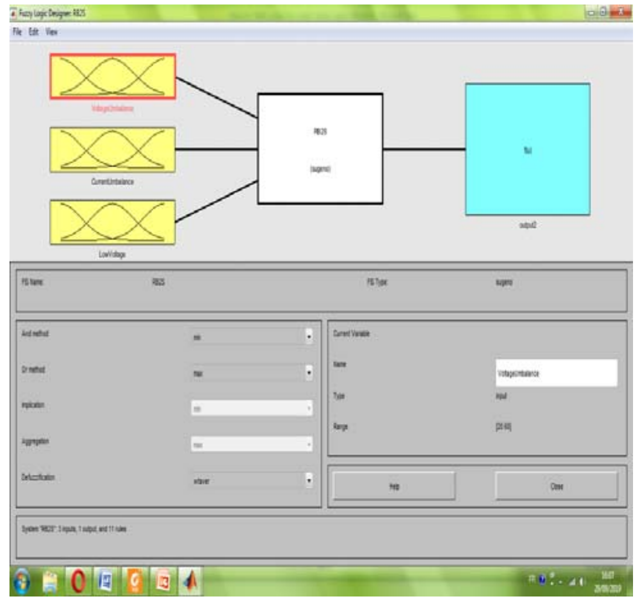

Fig. 4. Fuzzy logic designer for the second fuzzy controller

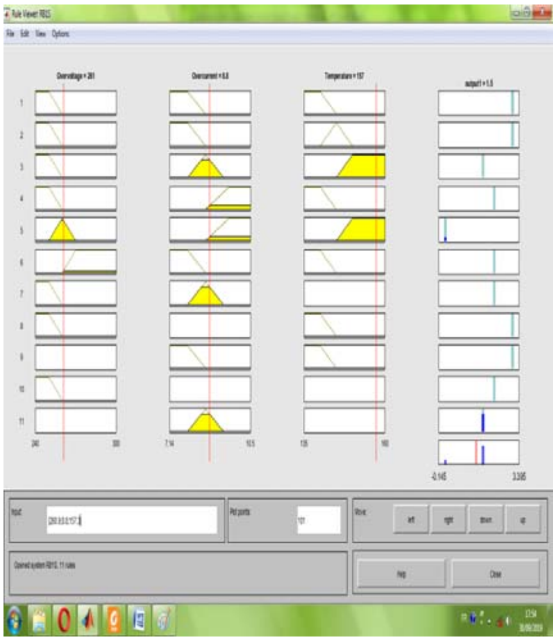

Fig. 5. Rule viewer of test N°2

Table 7. Second's controller results

N° test	Voltage unbalance (V)	Current unbalance (A)	Low voltage (V)	Output2 (s)
1	23.8	0.9	192.5	2.9
2	30.9	1.6	186.2	2.64
3	44.3	0.66	166.5	3
4	51.3	2.3	170.5	3
5	55.5	1.8	190.3	3
6	28.6	2.2	188.8	2.56
7	36.5	2.7	195.3	2.27

The figure below shows the outputs of the test N° 7.

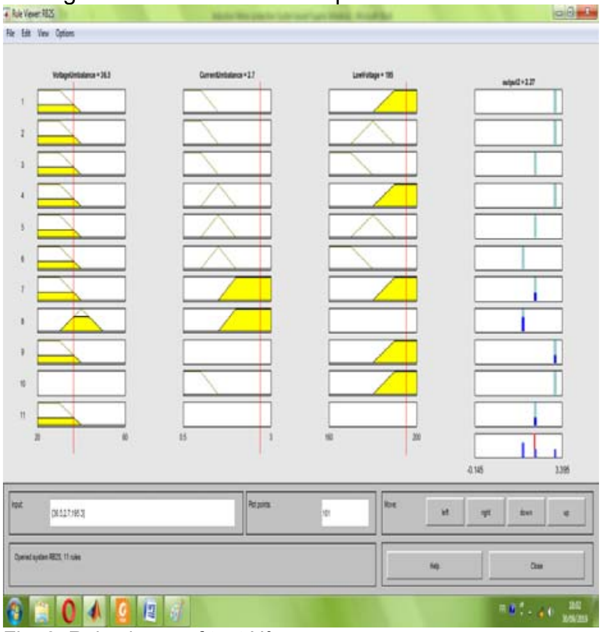

Fig. 6. Rule viewer of test N°7

Table 8. Final time delay values

N° test	Output1(s)	Output2(s)	Final time delay (s)
1	2.82	2.9	2.82
2	1.5	2.64	1.5
3	3	3	3
4	2.9	3	2.9
5	2.6	3	2.6
6	2.22	2.56	2.22
7	2.9	2.27	2.27

The table above shows the final time delay which represents the minimal value of the two controller's responses according to the equation below:

Final time delay= min (Output1, Output2)

According to the obtained results presented on table 5, table 6 and table 7, we can conclude that the proposed protection system for induction motor based on Sugeno Inference is interesting and could be implemented in industrial instead of the classical protection system where the time delay is adjusted constantly manually. Also, the proposed protection could inform the operator about the default nature.

Conclusion

This paper presents a protection system for induction motor based on Sugeno Inference detecting faulty operations for a three-phase induction motor. The proposed system provides an intelligent protection against overvoltage, over current, temperature, voltage unbalance, current unbalance, and under voltage. In the classical protection system, the time delay is adjusted manually according to the error type. The fuzzy protection system computes the time delay automatically according to the rules base. The proposed intelligent protection is easy to implement and can improves induction motors protection system.

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