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# Design of experiments for the adjustment of fuzzy logic-based controls of an Electrostatic Separation Process

***Abstract****. The main objective of this paper is to design an intelligent control to improve the separator process of electrostatic rotating electrode separator by fuzzy logic. Where the methodology of designing experiments was used to form a knowledge base, and from it extract the important variables and the way they affect the outputs, as well as the interaction between them and established the mathematical model by using Minitab 18 software, while the MTLAB programs were used to simulate the fuzzy control system. The results showed the ability of the controller to improve the separation process in a good time, which will lead to saving time and energy.*

***Streszczenie.*** *Głównym celem tego artykułu jest zaprojektowanie inteligentnego sterowania usprawniającego proces separatora elektrostatycznego separatora elektrody wirującej za pomocą logiki rozmytej. Tam, gdzie metodyka projektowania eksperymentów została wykorzystana do stworzenia bazy wiedzy, z której wyodrębniono ważne zmienne i sposób, w jaki wpływają one na wyniki, a także interakcje między nimi i ustalono model matematyczny za pomocą oprogramowania Minitab 18, natomiast MTLAB programy zostały wykorzystane do symulacji rozmytego systemu sterowania. Wyniki wykazały zdolność sterownika do usprawnienia procesu separacji w odpowiednim czasie, co przełoży się na oszczędność czasu i energii.* (***Projektowanie eksperymentów do regulacji opartych na logice rozmytej kontroli procesu separacji elektrostatycznej***)

**Keywords:** Electrostatic Separation; fuzzy logic; Design of experiments.
**Słowa kluczowe:** separacja elektromagnetyczna, logika rozmyta.

## Introduction

The waste electric and electronic equipment (WEEE) continues to increase [1], this poses a threat to humans and the environment [2]. Therefore, it's recycling is an important subject [3,4].The roll-type corona-electrostatic separator is the solution of choice for sorting granular mixtures containing plastic and metallic particles [5,6]. And to obtain satisfactory results, a good control strategy must be relied on, but the Electro-separation is a multifactorial process (constructive features and variables parameters) ,where the large number of variables and many interacting phenomena pose difficult problems to researchers To get to the optimum point [7], In such cases, the traditional control methods fail to optimize the operation of such equipment [8] .

On the other hand, however, artificial intelligence has proven its effectiveness in controlling the electrostatic separator on several occasions, such as [8] by using genetic algorithms, but the latter is for it time-consuming to evaluate, It is not recommended by many in the field of control compared to fuzzy logic and neural networks [9], and recently, an intelligent controller has been designed using Biogeography-based-optimization (BBO) and Neural networks [10]. To prove once again artificial intelligence techniques for their success in the control electrostatic separator. But It is known that these previous techniques are highly dependent on the accuracy of the available models, and any change in the model may lead to an imbalance in the outcome, this is very likely in the case of an electrostatic separator [11], due the ambient and experimental conditions granulometria of waste…..etc. On the other hand, fuzzy logic is a robust system where no precise inputs are required [12,13]. Besides that in a previous paper [14], the fuzzy logic had been reported as an effective tool for the control of electrostatic separator, although the control was limited as it relied on only one variable.

In this study, a fuzzy logic controller was designed based on three variables (high voltage, roll speed and feed rate), but as we know the fuzzy logic considered the expert knowledge the most important thing [15], however, with the variety of models available, with different characteristics of each electrostatic separator. It makes it impossible to rely solely on experience for fuzzy control or even relying on other studies.

To overcome this problem, we conducted a statistical study to create a knowledge base for use in control based on experiments from the paper [11], by using Design of experiments methodology technique [16] that have proven its efficiency in the field of electrostatic separator In many research papers such as [17,18].

## Knowledge base construction

To create a knowledge base about corona-electrostatic separator, we relied on a statistical study. To carry out this statistical study, we drew on experiments from the previous paper [10], where the variables are roll speed, the applied high voltage, and the feed rate ; the sample was 200 g (25% copper, 75% insulating materials, particle size > 1 mm and < 2 mm), while the domain of variation of the three variables is given in Table 1.

Table 1. Domain of variation of the control factors

| Factor | U [KV] | N [Tr/min] | m [Kg/ h] |
|---|---|---|---|
| Minimal value | 20 | 60 | 5 |
| Maximal value | 30 | 80 | 15 |

The outcome of the process are the masses of the compartments of insulator, conductor products and middling. The mass of compartments was relied upon as an output without taking into account only the pure mass of products to simulate industrial reality where is difficult to know the purity of the product; where the results proved that the laboratory electrostatic separator has the same characteristics as the separator used in the industry [19].

To implement the statistical study, the following steps were followed:

- Step 1: determine which terms are statistically significant and which terms contribute the most to the variability in the responses.
- Step 2: study how significant factors affects the responses.
- Step 3: study the significant interactions between factors and how effects on the responses.

In first step, we have adopted the result of Pareto chart where the Pareto chart contains a bar for each effect, sorted from most significant to least significant [20]. Bars that cross the reference line t are statistically significant, where t is the quantile of a t-distribution with degrees of freedom equal to the degrees of freedom for the error term.
The confidence level for all intervals is 95% for all tests α=5 %, where the results of the experiments were statistically analyzed using Minitab 18 statistical software.

***Insulator product***

In (Fig.1) the Pareto chart indicate that the effect of B has the highest standardized effect on the insulator product followed by A, AA, AB and C, as for the effect of factors AB and C they almost negligible compared to effect of others factors.

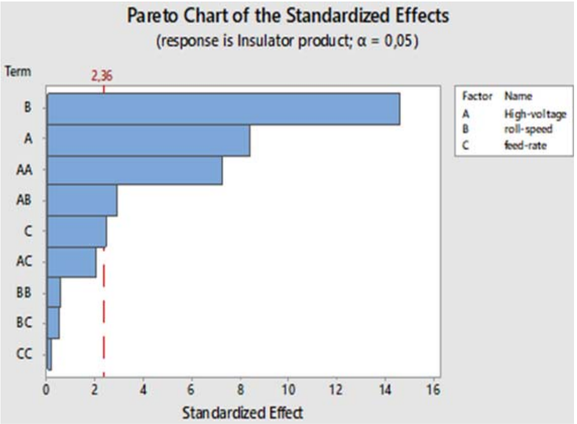


Fig.1. Pareto Chart of the Standardized effects for insulator product

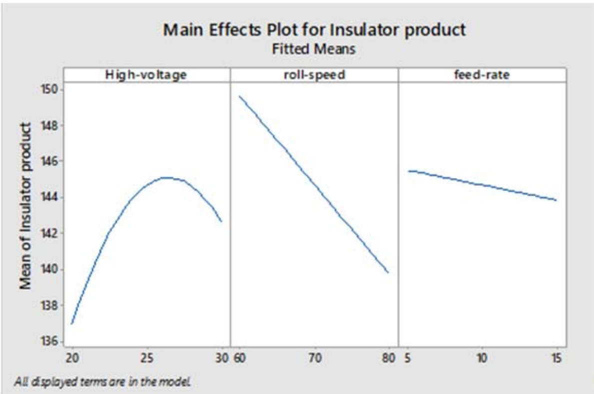


Fig.2. Main effect plot for the impact strength of insulator product.

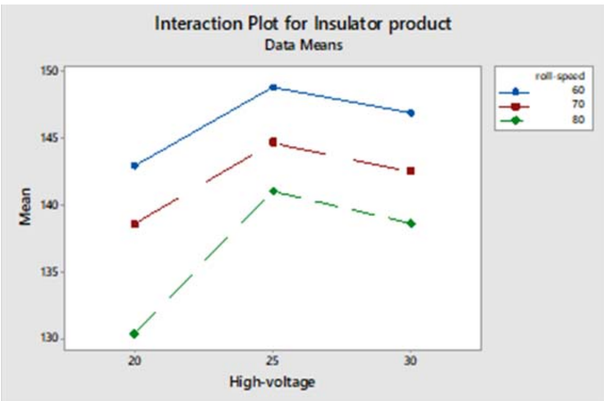


Fig.3. Plot of interaction effects for the impact strength of insulator product.

Form the Main effect in Fig.2 note at first, that the increase in voltage is offset by an increase in the recovery of the insulating product that's up to the fact of the good charge acquired by the insulator particles, therefore help it to pin to the rotating roll by the electric image force [21], but the effect of high voltage on the insulator product changes to negative after a certain value this probably due to spark discharges phenomena [22], which might have a negative impact on the charge acquired by the particles in the corona discharge field zone.

On the other hand, the roll-speed has a negative impact on the insulator product; this is due to the fact of the centrifugal force that which prevent the insulator particle to pin. Regarding The feed rate has a little negative impact into insulator product this probably due to contention of particles between them where it prevent each other to gain enough charge or pin to the rotating roll [23] .

For the interaction between the factors high voltage and roll-speed the (Fig.3) shown that the roll-speed have a little negative impact on the effect of high voltage only when the latter be in low level and the roll-speed in the high level. However, the interaction effect remains almost non-existent and cannot be relied upon in the control process in this paper. Contrary to some previous papers [8], which depended on this interaction, and the defect was compensated for in one variable by the other.

This result is almost identical to the theoretical side except the negative impact of high voltage, this probably due to spark discharges phenomena as mentioned above, this is difficult to predict theoretically.

Therefore, to for increase the recuperation of insulator product we must decrease the roll-speed and the feed-rate and increase the high-voltage with limit value.

***Conductor product***

The Fig.4 shows that main effects B (roll speed) and C (feed rate), interaction between roll speed (B) and feed rate (C) and the squared terms for roll speed BB are significant at 5 per cent significance level, unlike high voltage which has no effect.

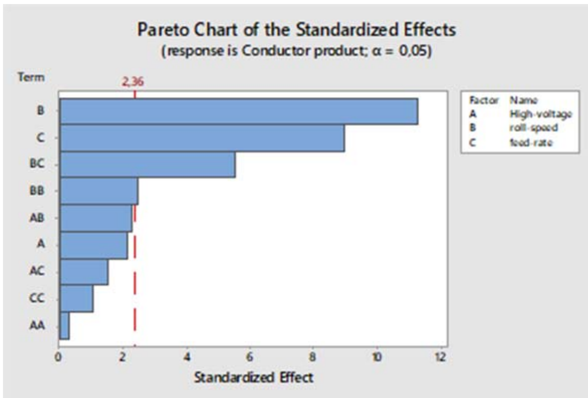


Fig.4. Pareto Chart of the Standardized effects for insulator product.

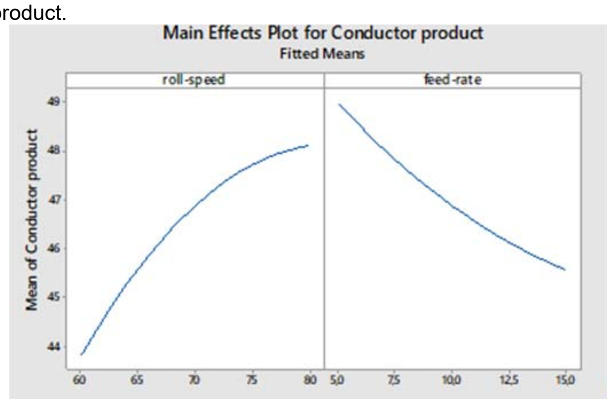


Fig.5. Main effect plot for the impact strength of conductor product.

As the Fig.5 shows, it is clear that when the roll speed increase, the conductor product increase; on the other hand, the feed rate has negative impact on the conductor product recuperation. We can mitigating the negative impact of feed-rate by increase the roll speed.

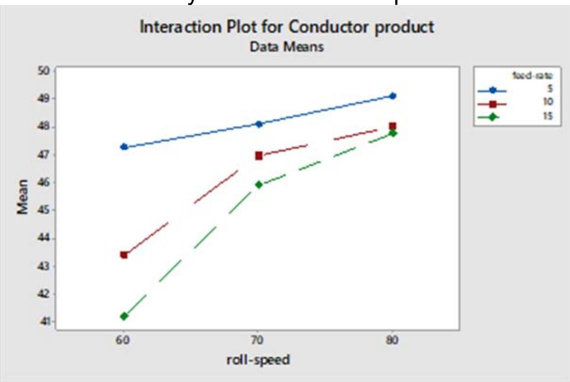


Fig.6. Plot of interaction effects for the impact strength of conductor product

From the interaction plots between feed rate and roll speed Fig.6 by increasing in the roll-speed, we scale down the negative effect of feed-rate.

The effect of roll-speed on the conductor product was expected due the centrifugal force [24], but it is quite interesting to note that high voltage on its own has no significant impact on the conductor product, this is the opposite of some of the results, both theoretical [24] and experimental [25], this probably due to the domain of variation of the high voltage considered in this experiments [11].

Therefore, to for increase the recuperation of conductor product we must increase the roll-speed and decrease the feed-rate.

***Middling***

For the middling The Pareto plot in Fig.7 has indicated that total significant factors on the conductor and insulator product are significant for the middling and the highest standardized effect is high voltage followed by roll speed (B) followed by C, AA and BC.

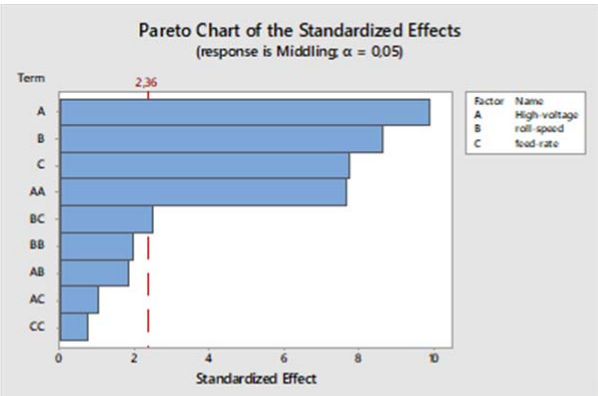


Fig.7. Pareto Chart of the Standardized effects for middling

Actually, if we combined the effect of the high-voltage and the squared terms for high-voltage we find that the high-voltage has the largest effect on the middling, that's too obvious in main effect plot Fig.8, as its effect on the middling is completely opposite to its effect on the insulator product, this is an indication that most of the wasted insulator product is directed to the middling compartment.

On the other hand, we notice that the higher the roll speed , the greater the mass of the middle with it, which is the lost insulating product, because with increasing speed the insulating product decreases and the conductive product increases, as we explained previously. Therefore, the amount of conductive product present in the medial compartment is only due to the increase in the feed rate. From this we conclude that the lost conductor due to lack of roll speed is heading directly to the insulator compartment; this is evident in the Fig.9, normal Plot of the Standardized effects of conductor collected in the insulator compartment. Where normal Plot of the Standardized effects displays negative effects on the left side of the graph and positive effects on the right side of the graph In contrast the non-significant ones fall along a straight line and tend to be centered near zero [12].

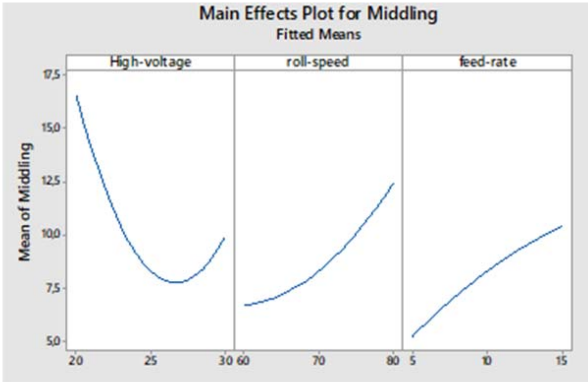


Fig.8. Main effect plot for the impact strength of conductor product.

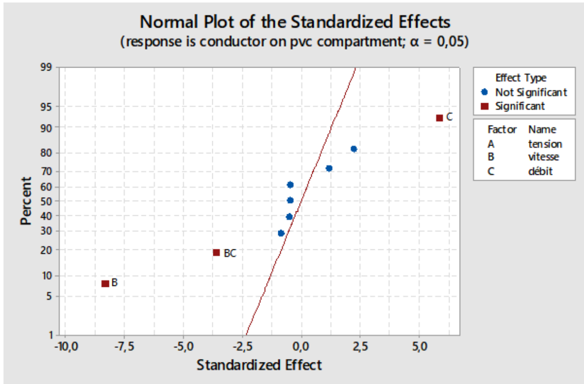


Fig.9.normal Plot of the Standardized effects of conductor collected in the insulator compartment.

## PROBLEM FORMULATION

The aim of controller is maximize insulator product *(Mi)* and the conductor product *(Mc)* and minimize the middle *(Mm)*, while maintaining the purity of the products *(Mi,Mc)*. Through the statistical study, we found that the high voltage *(U)* has impact on the *Mm* and *Mi* positively and negatively that's why we should have a good control for the high-voltage in first place .while the roll-speed *(n)* has positive impact on the *Mc* recover and the purity of *Mi* and negative impact on the *Mm*, As to the feed-rate has a negative impact on the *Mc* recover and purity of *Mi*.

So for the design of the controller, all of the above must be taken into account the double impact of high voltage on the insulator *(Mi)* and the middle *(Mm)*.The positive effect of roll speed on the recovery of the conductor *(Mc)* and the purity of the insulator *(Mi)*, is offset by a negative impact on the middle *(Mm)*.The feed rate does not need a controller, because it is evident from the analysis that the best separation process is at the lowest feed rate value. While the interactions between the factors were neglected to facilitate the rules of control, because their impact on the outcome is almost incomparable with the other factor.

To achieve the control system, the only reference we have is the percentage of middle $mm=0$ (Simulate the industrial side), while the percentage of conductor mc and insulator mi they cannot be identified in most cases, that is why we cannot confirm the validity and purity of separation.

It is possible that the middle ratio is small while the conductive product is directed into insulating product compartment, or vice versa where:

$$mi=Mi/(Mi+Mc+Mm) \quad mc=Mc/(Mc+Mc+Mm) \quad mm=Mm/(Mm+Mc+Mm) \tag{1}$$

Bypassing this problem is by observing the change in the ratio of Mi $(\Delta mi)$ with the change in the high voltage $(\Delta U)$. Where the high voltage controller stops increasing or decreasing $(U)$ where:

If $\Delta mi*\Delta U>0$ then Increase $U$
If $\Delta mi*\Delta U<0$ then decrease $U$ where:

$$\Delta U = U_{i+1} - U_i \ \ and \ \ \Delta mi = m_{i+1} - m_i \tag{2}$$

where $i$ is the cycle counter.

Thus, we were able to solve the problem of high voltage control. As for the roll speed, In order to increase $Mc$ and the purity of $Mi$ and decrease $Mm$ we need as inputs: roll speed $(n)$,$\Delta mi$ ratio of $Mi$, and ratio of Mc $\Delta mc$ where:
If $(\Delta mi<0)$, the controller will decrease the speed.
If $(\Delta mc>0)$, the controller will increase the speed.

In this way, the purity of the $Mi$ can be increased and the Mc recovery increases with less damage to the $Mm$ ,because as we previously noted, part of the conductive product goes to the chamber of the insulating product due of the low roll speed, On the other hand ,the increase in n contributes to the recuperation of the conductor and also the purity of the insulator.

So, the system starts with initial values $U_0$ , $n_0$ and m at the initial moment (cycle 0), the fuzzy logic controller (FLC) read the outputs and makes changes to the inputs $(U,n)$ by increment or decrement, depending on the situation, even reaching the optimum value, where at cycle 1.

$$U_1 = U_0 + x_1 \ \ and \ \ n_1 = n_0 + y_1 . \tag{3}$$

In general

$$U_i = U_{i-1} + x_i \ \ and \ \ n_i = n_{i-1} + y_i . \tag{4}$$

where $x$ and $y$ represent the output of FLC of High voltage and roll speed in respectively and $i$ is the cycle counter.

The Fig.10 shown block diagram of the fuzzy control system of the electrostatic separator.

**Process model**

The process model employed for the simulations was established by using the design of experiments methodology thus, the insulator ($Mi$) , the conductor ($Mc$) and the middling ($Mi$) were expressed as functions of the normalized centered value of the applied voltage $U$ , roll speed $n$ and the feed rate m as :

$$\begin{aligned} Mi &= 31.4+10.62U-0.357n-0.36m-0.2U^2 \\ Mc &= 11.3+1.139n-1.93m-0.008n^2+0.0222nm \\ Mm &= 133.1-11.32U+0.2870n+0.51m+0.213U^2 \end{aligned} \tag{5}$$

The Model summary given in Table 2

Table 2. Model summary

| | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| $Mi$ | 93,99% | 91,99% | 86,17% |
| $Mc$ | 92,75% | 90,34% | 81,46% |
| $Mm$ | 94,04% | 92,06% | 86,32% |

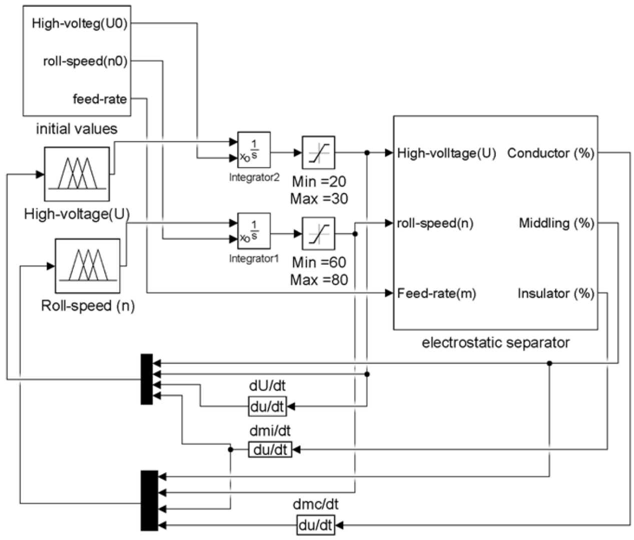


Fig.10. Block diagram of the fuzzy control system of an electrostatic separator.

R-sq: R2 is the percentage of variation in the response that is explained by the model.

R-sq (adj): Adjusted R2 is the percentage of the variation in the response that is explained by the model.

R-sq (pred): Predicted R2 is calculated with a formula that is equivalent to systematically removing each observation from the data set, estimating the regression equation, and determining how well the model predicts the removed observation.

**Fuzzy logic controller**

After creating a knowledge base, the Operation of a fuzzy controller can be divided into three steps [13] (Fig.11):

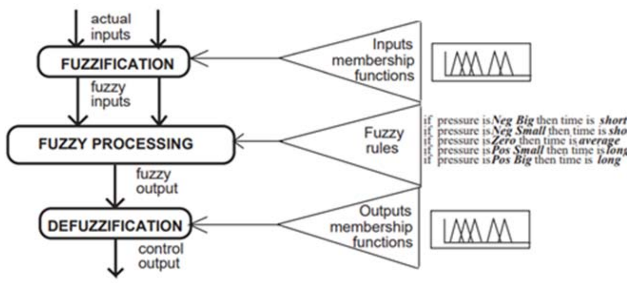


Fig.11. Operation of a fuzzy controller.

***Fuzzification of the input***

The fuzzification operation is quite simple. The grade of membership of each linguistic value is the truth-value of the fuzzy propositions [15]

The linguistic variables of input parameters are defined as in Table III. Where they presents the different range of the parameters together with their linguistic values.

To allow controlling the system the input ‘Middling’ is divided into ‘good’, ‘high’ and ‘very high’, where we considered the middling percentage could not represent more than 10% ,where the controller in this range (0-10 %) be more precise. Each variable Change in Percentage of middling, high-voltage, insulator and conductor can be divided into a range of states negative, positive as shown in Fig.12.The parameters High-voltage and Roll-speed are divided in two low and high.

Table III. INPUT PARAMETERS

| | Linguistic variables | symbol | Range | Linguistic variables | Parameters |
|---|---|---|---|---|---|
| Inputs | Middling (%) | $mm$ | 0-1 | good | 0- 0.1 |
| | | | | high | 0- 0.4 |
| | | | | Very high | 0.2- 1 |
| | High-voltage (kv) | $U$ | 20-30 | low | 20- 27 |
| | | | | high | 23- 30 |
| | Change in Insulator | $\Delta mi$ | -1- 1 | negative | -1- 0 |
| | | | | positive | 0- 1 |
| | Change in High voltage | $\Delta U$ | -1 -1 | negative | -1- 0 |
| | | | | positive | 0- 1 |
| | Roll-speed (tr/min) | $n$ | 60-80 | low | 60- 76 |
| | | | | high | 64- 80 |
| | Change in Conductor | $\Delta mc$ | -1 -1 | negative | -1- 0 |
| | | | | positive | 0- 1 |

We have chosen for each variable the triangular and trapezoidal shapes as shown in the Fig.12:

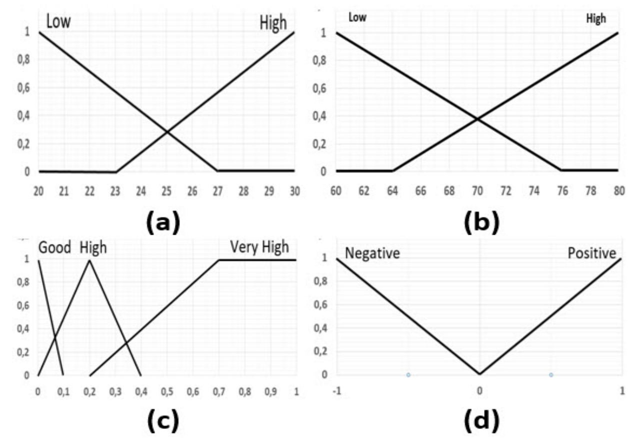


Fig.12. Input Membership functions: (a) the read value of high voltage. (b) The read value of roll-speed. (c) Percentage of middling (mm). (d) ∆U,∆mi,∆mc.

Fuzzy sets are defined through their membership functions. There are different types and forms of membership functions of a fuzzy set, but there is no standard method of choosing the proper shape of the fuzzy sets of the control variables. Trial and error methods are usually exercised [26,27], and professional experience and common sense [13].

### *Fuzzy processing*

Systems based on fuzzy logic use human knowledge presented in the form of fuzzy rules, also called rules of inference, to make decisions. Each rule delivers a partial conclusion which is then aggregated with the other rules to provide a conclusion [28].

The inference rules were extracted for both high voltage and roll speed. Briefly and accurately. So that all unimportant or meaningless rules have been neglected such as: IF (mm is good) and (U is …..) then (U is ……)

*Inference Rules*

*High-voltage*

Rule 1: IF (mm is very high) and (U is low) then (U is high-increase)
Rule 2: IF (mm is very high) and (U is high) then (U is high-decrease)
Rule 3: IF (mm is high) and (U is high) then (U is low-decrease)
Rule 4: IF (mm is high) and (U is low) then (U is high-increase)
Rule 5: IF (mm is good) and (∆U is positive) and (∆mi is negative) then (U is low-increase)
Rule 6: IF (mm is good) and (∆U is positive) and (∆mi is positive) then (U is low-decrease)
Rule 7: IF (mm is good) and (∆U is negative) and (∆mi is positive) then (U is low-increase)
Rule 8: IF (mm is good) and (∆U is negative) and (∆mi is negative) then (U is low-decrease)

*Roll-speed.*

Rule 1: IF (mm is very high) and (n is high) then (n is high-decrease)
Rule 2: IF (mm is very high) and (n is high) then (n is high-decrease)
Rule 3: IF (mm is good) and (n is low) then (n is increase)
Rule 4: IF (mm is good) and (∆mi is negative) then (n is decrease)
Rule 5: IF (mm is good) and (∆mc is positive) then (n is increase)

### *Defuzzification*

In the process of defuzzification, convert the fuzzy output variable back to the crisp variable for the control objective. Generally, defuzzified output has to be the most appropriate solution. The two mechanisms are the maxima method, which looks for the highest pack, and the centroid method, which relies on determining a property's balance point [29]. The present study uses the centroid approach.

Similarly as inputs, the linguistic variables of outputs are defined as in Table IV.Where the high-voltage divided into high decrease, low decrease, low increase and high increase to make the control more smooth and precise. While the roll speed divided into a range of state increase and decrease, the diagram in Fig.13 shows the membership functions related to a typical fuzzy controller's output variable.

Table IV. OUTPUT PARAMETERS

| | Variables | Symbol | Range | Linguistic variables | Parameters |
|---|---|---|---|---|---|
| Outputs | High-voltage | HV | -5 -5 | High-decrease | -4 -3 |
| | | | | Low-decrease | -1- 0 |
| | | | | Low-increase | 0- 1 |
| | | | | High-increase | 3.5 – 4.5 |
| | Roll-speed | RS | -5 -5 | High-decrement | -4- 2 |
| | | | | High-increment | 2- 4 |

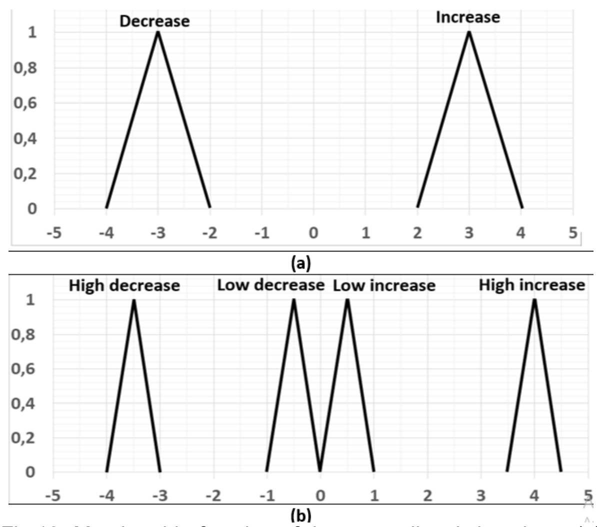


Fig.13. Membership function of the output linguistic values: (a) high-voltage control (b). (f) roll-speed control (y)

### Simulation results and discussion

### *Response of the System at fixed roll-speed and different feed rate value.*

The result of first simulation shown in Fig.14, we only controlled the high voltage value, while manipulating the feed rate value, where the roll speed fixed in 60 rev/Min, the FLC succeed to optimize the system in eight cycles, where was maximized the mi even 74.7% ,which is equivalent to 99.6%, and minimized mm even 1.3% at a high voltage U=26.5KV, but without significant impact on mc. Because as we know that the total ratio of the insulating product is 75 % and 25 % for the conductor product .

However, the increase in the value of the feed rate m negatively affected both mc and mm, but without significant impact on mi. We also noticed that the high voltage U did not interact with the increase in feed rate m.

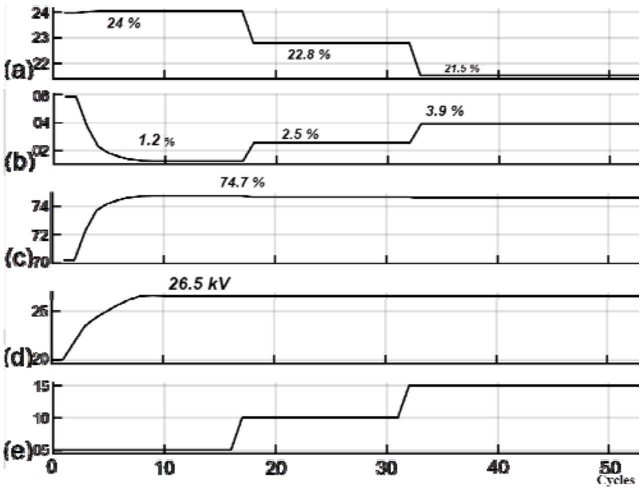


Fig.14. Results of simulation of fuzzy controller operation with n fixed at 60 rev/min. (a) the change in the percentage of the conductor product. (b) The change in the percentage of the middling product. (c) The change in the percentage of the insulator product. (d) Adjustment of the applied voltage. (e) Feed rate value.

***Studying the response of the system by controlling two variables with intentional distortion***

The second simulation Fig.15 is aimed at controlling both speed and high voltage, and shows the reaction of fuzzy logic controller in different value of feed rate, and with an artificial perturbation on high voltage in cycle 32, and roll speed in cycle 42.

Through Fig.15, we note that the FLC needed eight cycles to set the optimum value for high voltage ,while it took 14 cycles to set the roll speed and thus the system as a whole, the results shown on Table V. As for the interaction of FLC with different values of the feed rate, we notice that FLC kept the optimum value for high voltage constant, while the speed was decreased as the value of m increased to minimize the negative impact of feed rate augmentation on mm, but without a noticeable effect on mc.

Table V. Results of simulation of fuzzy controller operation.

| | M=5 Kg/h | M=10 Kg/h | M=15 Kg/h |
|---|---|---|---|
| Conductor % | 25 (100%) | 24.3 (97.2 %) | 23.5 (94 %) |
| Middling % | 3.1 | 4.3 | 5.4 |
| Insulator % | 71.7 (95.6 %) | 71.3 (95 %) | 71 (94.7%) |
| High voltage (Kv) | 26.5 | 26.5 | 26.5 |
| Roll speed (rev/min) | 73.5 | 72.5 | 71.6 |

Compared with previous results in Fig.14 with fix value of roll speed (n=60 rev/min) and through the recorded result in Fig.15 we noticed an augmentation on percentage of middling and conductor and diminution of insulator on the other hand. This is due to the strategy adopted on control, considering recover of conductor and purity of separation processes as priority.

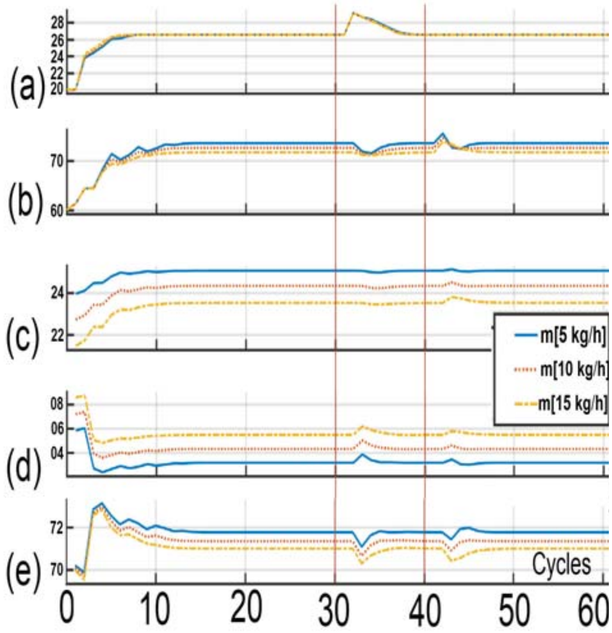


Fig.15. Results of simulation of fuzzy controller operation. (a) Adjustment of the applied voltage. (b) Adjustment of the roll speed. (c) The change in the percentage of the conductor product. (d) The change in the percentage of the middling product. (e) The change in the percentage of the insulator product.

At cycle 32 we perturbed the high voltage by inject a 3 KV on the stable value (U=26.5 KV),we registered a fast reaction from the FLC, where it needed to three cycles to adjust the optimum high voltage value again , was also has been Decreased the roll speed value Temporarily to adapted to new situation. Where it save somewhat the optimum point on mm and mi with slight decrease on mc.

Similarly, at cycle 42, we perturbed the roll speed by added 2 rev/min on the optimum value, the FLC quickly adjusted the optimum roll speed value on the next cycle (cycle 43).but we didn't notice any change in high voltage value. Because any increase or decrease in the value of the high voltage will adversely affect the separation process.

The results registered proved the feasibility of FLC under different circumstances particularly the high voltage, due to their reliance on middle percentage.

**Conclusion**

Relying on experience alone or previous studies related to other electrostatic separators of the same type in the design of the controller may be insufficient. Especially since the fuzzy controller relies heavily on the designer's information. And sometimes even a database collected from the same electrostatic separator is not useful if the field of study for the variables differs. Which is why the results presented in this paper are strictly valid only for this separator and only for domain of variation of variables considered in this experiments. Therefore, doing a prior study before designing any control is necessary and very useful.

Studying the interaction of variables with each other is very important. In theory, the damage caused by confusion in one variable can be compensated by another variable. It is a common occurrence in the electrostatic separator control process, but this is not possible in all cases. For example, in this paper there is no interaction between roll speed and high voltage.

The fuzzy controller is a powerful controller and does not need precise inputs. This gives it an advantage for the good control of the electrostatic separator in various conditions. The optimal solution may differ slightly from one experiment to another due to uncontrolled elements such as the percentage of moisture and the size of the product to be separated ... etc.

As the separation results obtained by the fuzzy controller are satisfactory. And the transfer of this technology to the industrial field will yield a great benefit in terms of saving time, energy and labor, as well as a benefit to the environment.

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