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ON-LINE PREDICTION OF PHOTOVOLTAIC OUTPUT POWER UNDER CLOUDY SKIES BY USING FUZZY LOGIC

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Abstract:

This paper presents an on-line prediction technique of the photovoltaic output power under cloudy skies based on artificial intelligence. The technique takes advantage of the fact that fuzzy logic can accurately simulate non-linear phenomena using a set of IF-THEN rules. These rules are fired partially and in-parallel. This means that, at any time, only a very limited subset of the rules is used. This enables a quick, on-line estimation of the output power of the photovoltaic cells based on the analysis of the image of the cloudy sky.

1-Introduction:

It is common practice to make load priorities for any limited power supply grid. With increased demand, some of lower priority loads are to be shed. In stand alone photo-voltaic systems, varied priority loads may be manipulated, if previous knowledge of input power is obtained specially under cloudy skies. The proposed method is based on 106 cases of cloud cover photos taken using a wide- angle lens, with the center of the frame directed to the virtual position of the sun. A measurement scheme was devised to relate the frame to the predicted output based on gray scale template for each pixel in the frame on the average, first moment and the average of the pixel weight multiplied by the cosine of the ray, normal to the panel.

In real time applications, it may be necessary to make a quick decision about the load priority in order to save battery stored energy by switching off pre-scheduled lower priority loads in case of cloudy skies.

A stand-alone photovoltaic power system is made of an array of solar cell modules and storage batteries. In the design of a standalone system, a large capacity is used to provide high reliability. The solar system cannot produce its maximum output power over the year, especially in winter months. In this case, we have to make switching decision between high and low demand loads [1]. An artificial intelligence technique, based on fuzzy logic, will be used in the on-line decision.

2-Fuzzy logic theory:

Fuzzy logic is a quantification of ambiguity and vagueness. The point of fuzzy logic is to map an input space to an output space. A membership function defines the degree of which an element (x) of the set (X) is included in this set $0 \leq \mu_A \leq 1$.

Fuzzy sets depend on fuzzy rules, which take the form of conditional statements in the form of IF-THEN rules [2][3][4][5].

IF x is A THEN y is B, where A and B are linguistic variables defined by fuzzy sets on the range (universe of discourse) X and Y respectively. The IF part of the rule is called antecedent or premise, while the THEN part of the rule "y is B" is called the consequent or conclusion. The inference method used to represent individual degrees of support is based on approximate reasoning.

After fuzzification all rule premises are calculated in parallel and partially. The rules themselves are useful because they refer to variables and the adjectives that describe those variables. The rules are evaluated by using the minimum operator for the representation of the linguistic (AND) and the maximum operator for the representation of the linguistic (OR).

Next, the degree of validity of the premise is weighted with the individual degree of truth for the conclusion. All conclusions are combined using the maximum operator.

Finally a defuzzification method is used to obtain a crisp result.

The popular methods for defuzzifying the output are:

1-Max-membership principle.
2-Centeroid method.
3-Weighted average method.
4-Mean-Max membership function.

Fuzzy systems are built using two methods: Mamdani fuzzy inference method or Sugeno- Takagi method. In our work Mamdani fuzzy inference method was adopted because it is more intuitive, better suited to human input and has obtained wide spread acceptance [2][3][4][5][6][7].
The main advantage of a fuzzy inference system is that all rules are fired partially and in parallel. Partially means that, regardless the total number of rules in the rule base, there is always a limited number of rules that are fired at a time. For n input universes of discourse partitioned with 50% over-lap, only 2^n rules are fired at any time. Parallel means that these 2^n rules are fired at the same time [3][4][5][6][7]. In other words, this means that, for a system defined on 3 universes of discourse, only 8 rules are fired at a time.
Any fuzzy system passes by the following steps:

1- Fuzzification of all input variables.
2- Execution of fuzzy rules.
3- Defuzzification of output variables.

3-Experimental procedures:

A commercial photovoltaic panel was set flat on the ground and was connected to a variable load resistance. A suitable time was chosen when the clouds covered the sky. A photograph was snapped with the frame center directed toward the sun using a Kodak film with 100 ASA. The Nikon camera with 22mm wide-angle lens with speed of 1/60 Sec and an opening of 8 is used. The maximum o/p power was measured by varying the value of the load. Short circuit current and open circuit voltage for each image was also obtained.
All images are scanned and MATLAB program is used to analyze each image with a gray level matrix for each image and statistical parameters are computed. Dull images, as sampled by figure (1), can be treated using three statistical parameters.

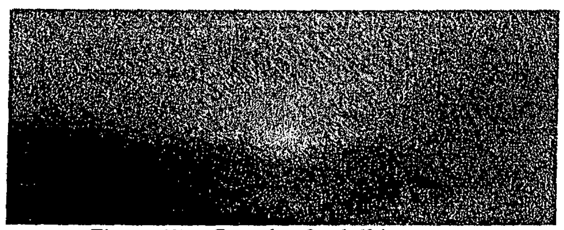
Figure (1) – Sample of a dull image

The first parameter is the average for all pixels.

$$\text{Average} = \overline{m} = \frac{1}{N \times M}\sum_{i}^{N}\sum_{j}^{M} P_{i,j}$$

Where : N*M= Size of matrix P.

i and j = Coordinates in horizontal and vertical directions.

$P_{i,j}$ = The number of colour corresponding to the pixel located at (i,j)

The second parameter is the average of the first moment at the center (n/2,m/2) of the image, which is described by the number of colour for each pixel multiplied by the distance from the center of image:

$$\overline{m_1} = \frac{1}{N \times M}\sum_{i=1}^{N}\sum_{j=1}^{M} P_{ij}\sqrt{(\frac{N}{2}-i)^2+(\frac{M}{2}-j)^2}$$

with the objective to include the distance of the pixel from the center.

The third parameter is the average pixel grade weighted on the cosine of the angle between the ray and the normal to the panel. This can be obtained from the matrix with the introduction of a correction factor (2/3) depending on the view angle of the lens used.

The inclination effect can be accounted for as follows:

$$\overline{P\cos\theta} = Ap = \frac{1}{M \times N} \sum_{-N/2}^{+N/2} \sum_{-M/2}^{+M/2} P_{ij} \frac{1}{\sqrt{1+\frac{4}{9}[(\frac{2n}{N})^2 + (\frac{2m}{M})^2]}}$$

Where

Ap: is the average projection of radiation to the normal of the panel.

$M \times N$= size of matrix.

i,j = location of any point of pixel.

4/9= View angle correction factor of the lens.

$P_{i,j}$ = gray scale number.

Fuzzy logic is applied, by considering the previous parameters as input to expert system to asses the incoming data and deciding between the lower and higher priority power supply demand.

In fuzzy systems each variable is fuzzified using linguistic terms such as (low, medium, high) which include all values from minimum to maximum. Each input has a universe of discourse which is equidistantly partitioned using triangular membership functions with 50% overlap as shown in figure (2). Mamdani approach is followed for building the system. All rules are evaluated with minimum operator (AND) and the degree of validity is weighted for each rule, and there is some rules more effective than others. Our system is a three dimensional system with three inputs (average, first moment, angle projection (Ap) and one output (I_{sc}). The rule base can be visualized as a cubic lattice with each input universe of discourse represented along one of the axis with its equidistant partitions. All results are combined and defuzzified by the centroid method that depends on the calculation of the area under the curve and get the center of gravity [2][4].

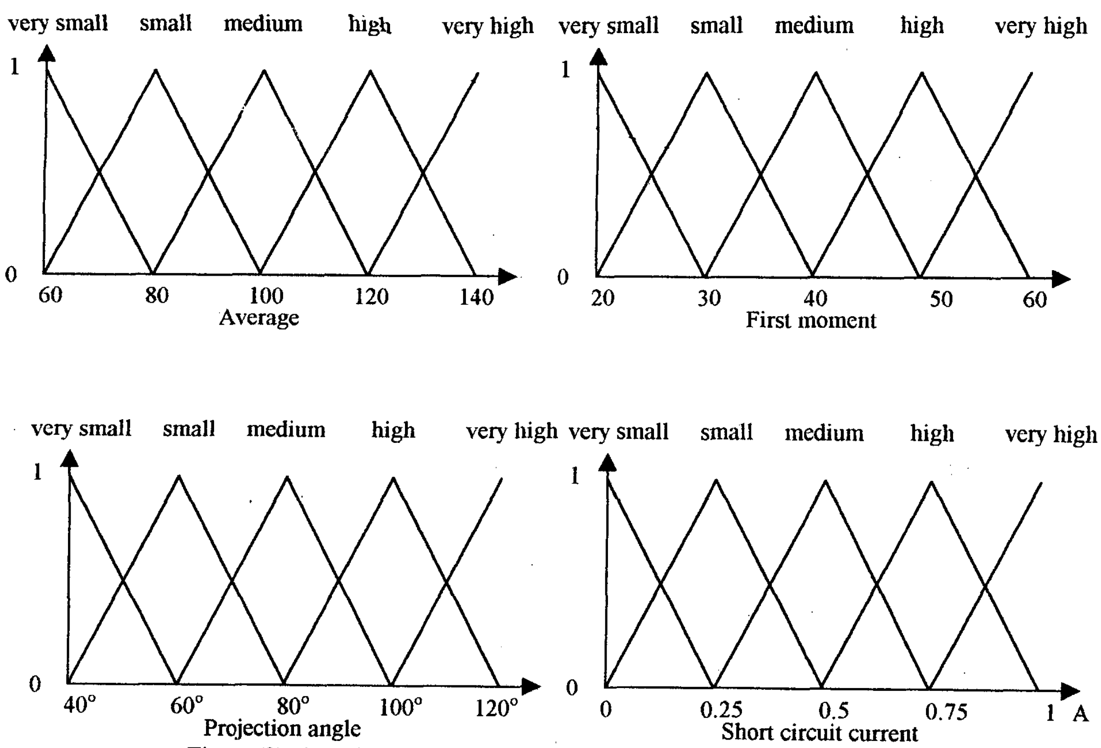

Figure (2) - Membership functions for all input and output variables

4-Results:

After defuzzification, the fuzzy values for short circuit currents have been extracted. This means that each short circuit current has two values an actual value (experimental value), which is measured by experiment, and a fuzzy value, which is obtained by the fuzzy algorithm. By making comparison between them, in rare cases the fuzzy values obtained by fuzzy simulation diverged from the experimental values. But in all other cases there is a slight difference between actual value and fuzzy value of about ± 0.05.

The comparison between actual value and fuzzy value is considering by two ways [8]:

The first way: by calculating the mean error and standard deviation [9].

The Mean Error $\overline{X} = 0.0342193$.

The Standard Deviation $\sigma = 0.033123$.

The comparison reveals that only 5 readings out of 100 readings have shown noticeable divergence.

The second way: is by comparing the plane constituted by the experimented results to that obtained by fuzzy simulator. The surfaces shown in figures (3-1), (3-2) and (3-3) are drawn for projection angles $A_p < 49°$, $49° < A_p < 66.5°$ and $66.5° < A_p < 112°$ respectively. The Euclidean space is made from the average along one axis, the first moment along the second axis and the short circuit current along the third axis. The experimental and fuzzy simulated data showed the same topological trends.

5-Conclusion:

Fuzzy logic is nonlinear in nature and is the best suited to model nonlinear functions of arbitrary complexity for a non-model based system. In our case only 8 rules are fired at any time out of a rule base made from 125 rules. It is worth mentioning here that a finer partitioning of the universe of discourse will not increase the number of fired rules. All rules are fired partially and in parallel. This leads to fast decision in real time applications. This application is concerned about the prediction of short circuit current of a stand alone photovoltaic system, in case of cloudy weather. A digitizing video camera can be connected to a microcomputer and the snapped picture can be analysed on-line. At this moment fuzzy logic can predict a drop in the o/p of the panel. Lower priority power demand loads are shed, such as water pumping, and then the storage battery supplies power loads of higher piority, such as illumination. If the clouds become scattered or tend to clear weather, and a higher output power is predicted, supply to lower priority loads can be resumed.
A complete system, starting from how to predict maximum output power, how to select the most significant statistical parameters ending with control and taking the decision with required power according to cloud weather condition is introduced in this paper.

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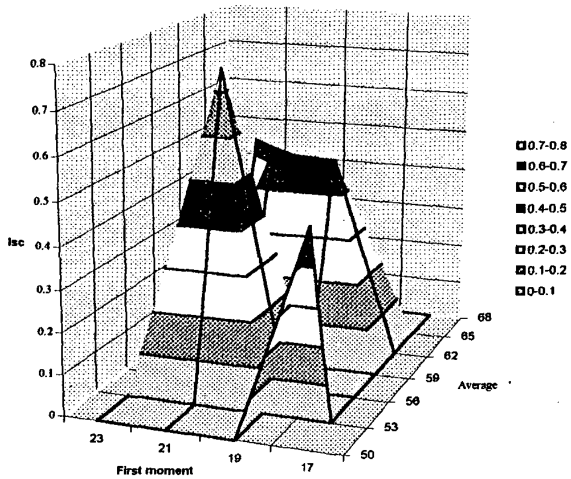
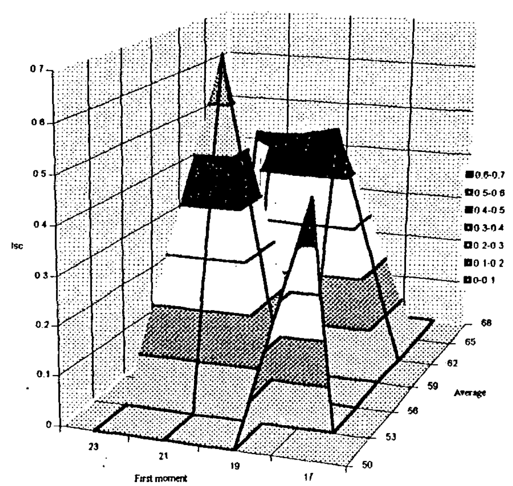
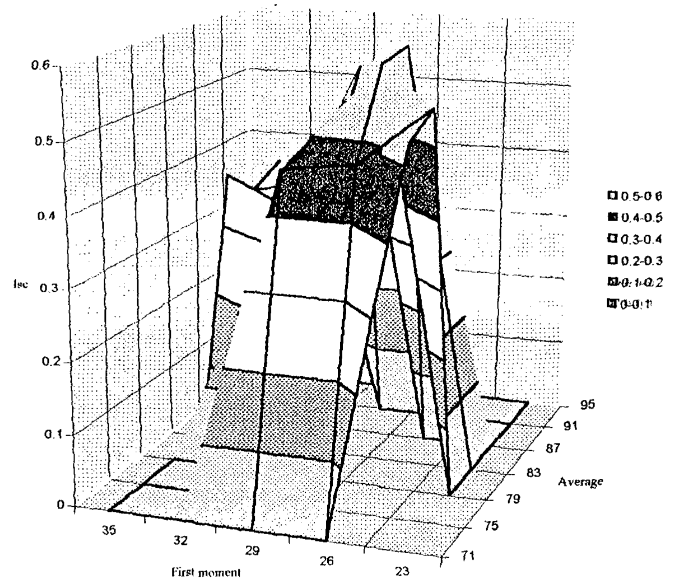


Fuzzy results for $A_p < 49^\circ$

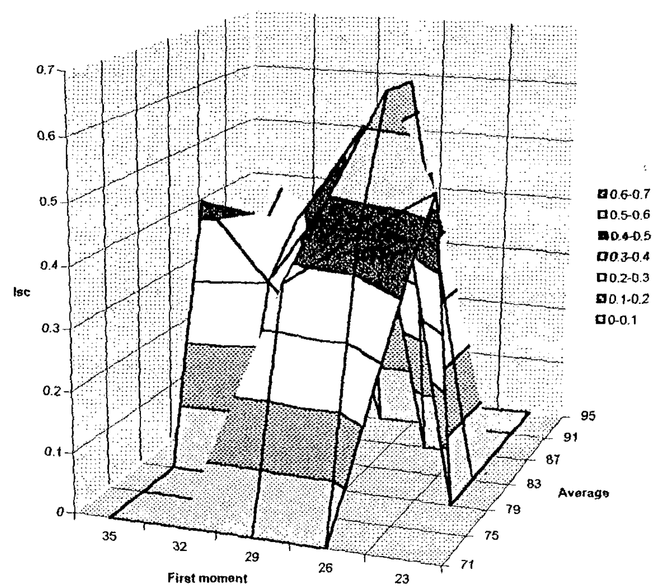


Experimental results for $A_p < 49^\circ$

Figure (3-1) – Comparison between fuzzy and experimental results for $A_p < 49^\circ$

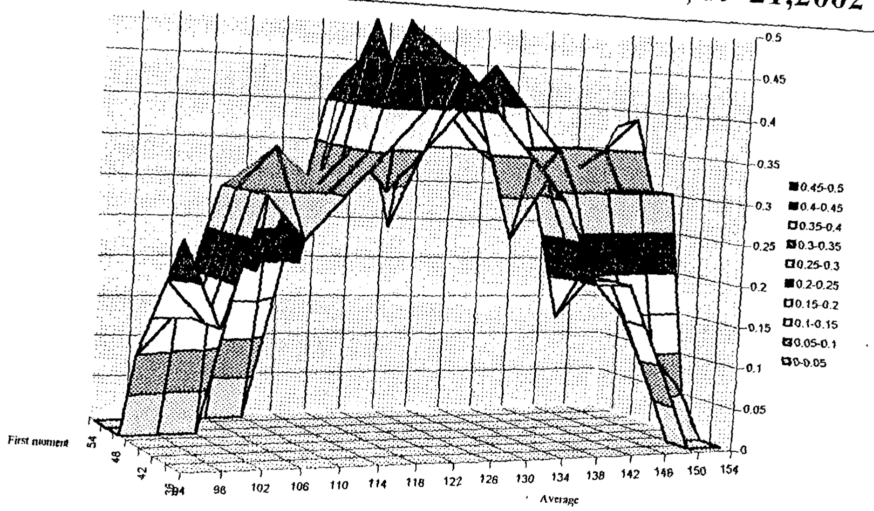


Fuzzy results for $49^o < A_p < 66.5^o$

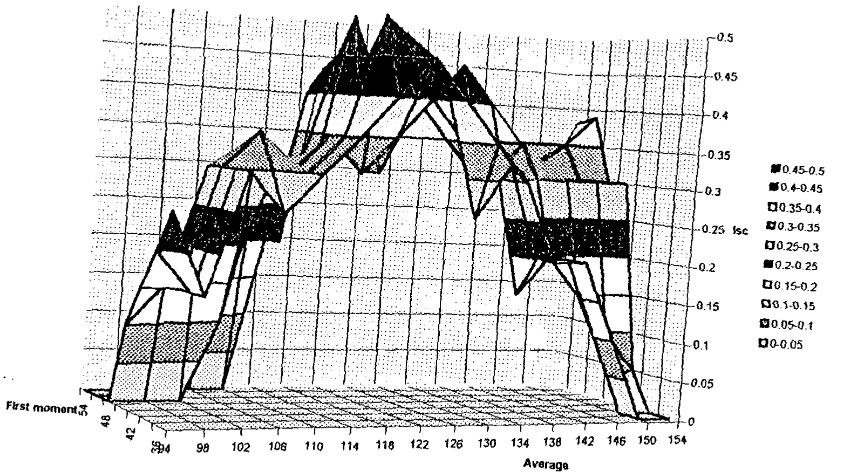


Experimental results for $49^o < A_p < 66.5^o$

Figure (3-2) - Comparison between fuzzy and experimental results for $49^o < A_p < 66.5^o$



Fuzzy results for $66.5° < A_p < 112°$



Experimental results for $66.5° < A_p < 112°$

Figure (3-3) - Comparison between fuzzy and experimental results for $66.5° < A_p < 112°$