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Supervising control system for oriented PV using weather forecasts

Abstract: This paper is devoted to the problem of controlling an oriented PV using weather forecasts. The described solution presents the use of fuzzy logic fundamentals in order to increase the efficiency of a PV system. It differs from most related papers in the fact that it uses fuzzy logic in order to process weather condition numeric values as input data. All of necessary steps to reproduce the proposed solution have been included.

Keywords: *photovoltaic cell, fuzzy logic, weather forecast, supervising control, artificial intelligence*

1. Introduction

Solar energy is the fourth-most-used source of renewable energy (right after hydropower, wind power, and biomass energy). Recent trends indicate its potential growth from 2.4% in 2015 to nearly 20% of the overall use of renewable energy by 2020 [3]. Despite the fact that it is the most generous source of energy due to its dispersion, it is not the most utilized one. The main issue for collecting energy via PV systems is the weather conditions. Each PV system is strictly dependent on the overall cloudiness or wind speed (for example), which can potentially affect the efficiency of such systems.

In this paper, a proposal for creating a supervisory control of oriented PV systems with the use of short-term weather forecasts is described.

The proposed solution is based on a single source of forecasts and implements a fuzzy controller in order to select the most suitable control algorithm for a PV system.

2. Motivations

As previously mentioned, weather strongly influences the work of PV systems when conditions change during the daylight hours. The energy effectiveness of PV systems have

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been evaluated at between 19% to 35%. In overcast conditions, it is possible to obtain a negative value of its energy effectiveness ratio (due to the energy consumed by PV systems while reorienting).

The implementation of a fuzzy controller to maximize the energy efficiency of a PV system was presented in [2]. An approach to a model PV system with fuzzy logic based on an MPPT algorithm was presented in [1]. The described solution presents a different approach to fuzzy logic usage. It is not used to improve the internal mechanism of PV work but rather to maximize the time of sun exposure and minimize the use of energy by the system itself.

The main motivation of this paper is to introduce short-term weather forecast with the use of a fuzzy logic-based algorithm in order to minimize the number of reorientation movements of a PV system as a means of reducing power consumption. This paper provides only the theoretical fundamentals for physical tests of the power consumption of the considered system. None of the tests have been described in this paper. Also, lower power consumption has not been proven in this paper.

The paper is organized as follows: first, elementary information about PV control and fuzzy control is recalled. Next, the proposed solution is presented with details. Finally, an example of the proposed system is presented.

3. Preliminaries

For the purpose of reorienting (re)orientable PV systems, there are four types of algorithms that can be applied [4].

- Time-based algorithm: reorients PV according to a specified trajectory depending on day of the year and geographic location. The priority is energy consumption.
- Storm algorithm: activated irrespective of factors other than strong wind. Priority is the offset time to horizontal position.
- Rain algorithm: sets PV into horizontal position (identical to the storm algorithm), but its priority is energy consumption.
- Sensor-based algorithm: applied to avoid cloudiness. The quality indicator describes both the energy consumption and reorienting time. It can be used when the collected information is not sufficient to choose one of the aforementioned algorithms.

A fuzzy controller can be described as a specified use case of fuzzy logic in order to compute the demanded control value. Constructing a fuzzy controller is comprised of three steps:

- create the membership function of the input,
- specify the fuzzy rule table,
- determine the procedure for defuzzyfing the result.

In the described solution, two inputs were determined: the value of the cloudiness and the wind speed value. The most common defuzzification algorithm is Mamdani's Center of

Gravity method. In this paper, this method has been chosen due to its “democratic” character. In the Center of Gravity method, all active fuzzy rules participate in the defuzzification process. This guarantees sensitivity when changing its inputs.

The membership functions described later in this paper are based on the aforementioned values of the inputs. All algorithms besides the storm algorithm have determined membership functions. As previously mentioned, the storm algorithm only depends on the value of wind speed.

4. Proposed solution

In this section, the proposed solution is described. The proposed system can be treated as a composition of three modules:

- Forecast analytical module – extracts numerical data from the short-term forecast (stored in a png format file). More details in Subsection 4.1.
- Steering module for extracted data (supervising control algorithm for PV systems). More details in Subsection 4.2.
- Fuzzy Logic rules definition. More details in Subsection 4.3.

The general schema of the system architecture is presented in Figure 1.

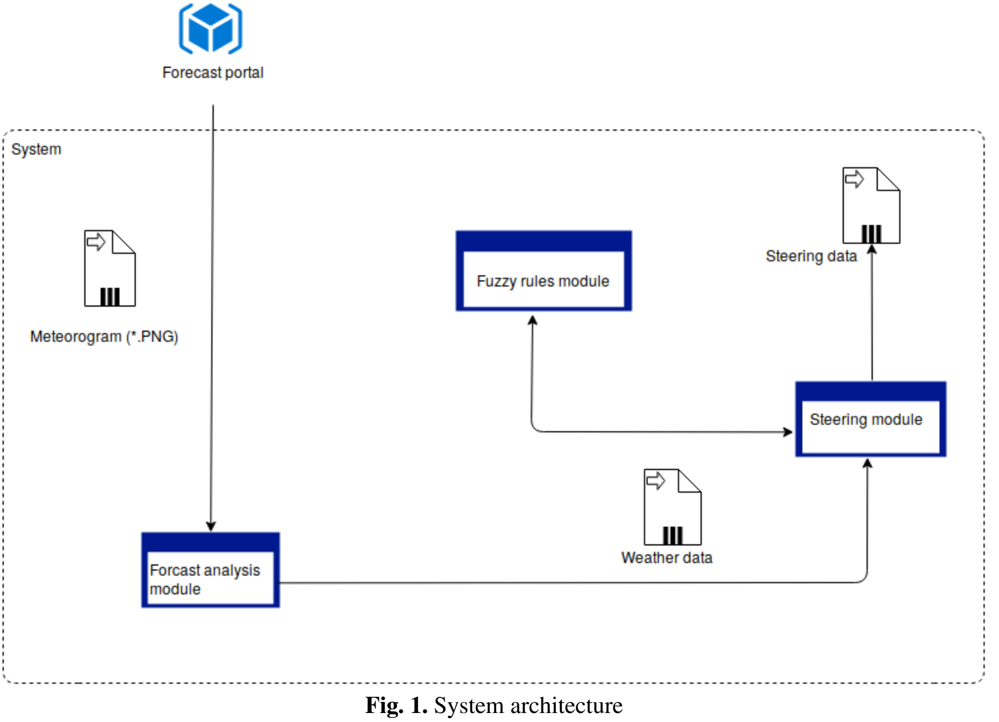

Fig. 1. System architecture

4.1. Forecast analytical module

As a source of weather data, the numerical weather forecast of ICM Warsaw University (www.meteo.pl) has been applied. The author used only one model of forecast: Model UM, grid 4 km, forecast length 60 h. A caption for the example forecast is presented in Figure 2.

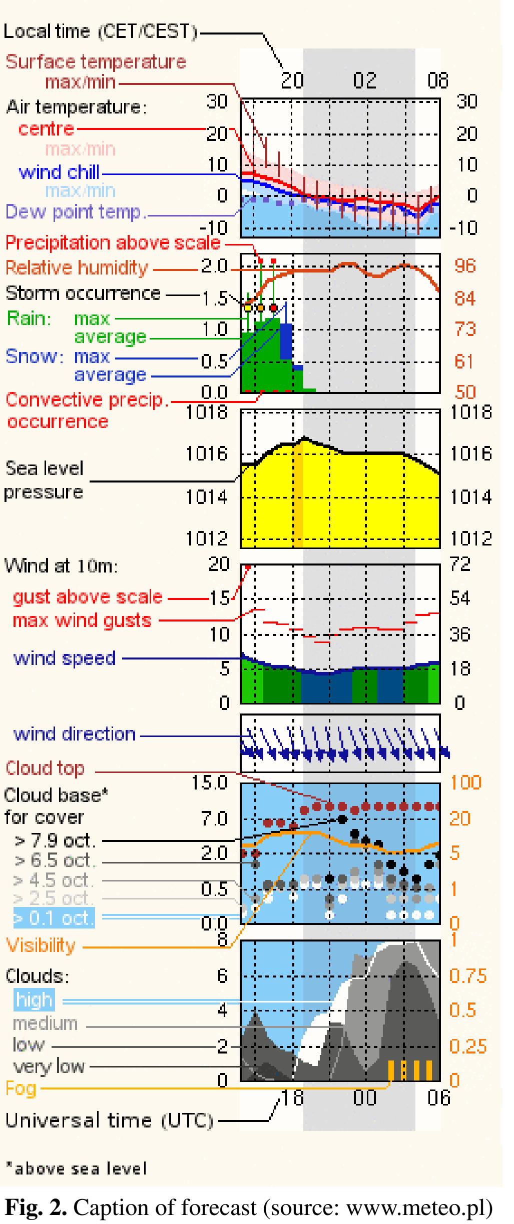

Fig. 2. Caption of forecast (source: www.meteo.pl)

Only two sections of the forecast picture from the presented model are relevant for the proposed control strategy. These are:

– cloudiness (octas),
– wind speed (km/h).

Numerical data extraction

The extraction of numerical data is done by parsing the png file (pixel by pixel) using color recognition for the values of cloudiness and wind speed. The format of the output data has been composed as follows:

– timestamp (format: YYY-MM-DD HH:MM:SS),
– percentage of cloudiness of low clouds (0.01 precision),
– percentage of cloudiness of medium clouds (0.01 precision),
– percentage of cloudiness of high clouds (0.01 precision),
– average wind speed in km/h (0.01 precision),
– maximum wind gusts in km/h (0.01 precision).

An example row of the extracted data has the following form:

2017-09-01 00:08:44;1.28;73.1;62.8;1.54;3.33

As can be observed, each value is separated with a semicolon. The collected data is stored in a CSV file and passed as an input argument for the supervising steering module. Implementation of the currently described module has been done with the use of Qt C/C++ development tools.

4.2. Steering module

The key responsibility of the steering module is to select a PV control algorithm suitable for execution during the forthcoming weather. A crucial element of this module is fuzzy logic rules. It requires normalized values of weather forecasts as input arguments (a more detailed description takes place in Subsection 3.3). Normalization takes place for two values from the forecast data file:

1) Cloudiness, with function:

$$CloudNorm(x) = \frac{(0.65 \cdot L(x)) + (0.25 \cdot M(x)) + (0.1 \cdot H(x))}{100} \tag{1}$$

2) Wind speed, with function:

$$WindNorm(x) = \frac{AvgWind(x)}{WindMax} \tag{2}$$

The explanations of formulas (1) and (2):

x – stands for value of timestamp,
L(x) – stands for percentage of cloudiness of low clouds,
M(x) – stands for percentage of cloudiness of medium clouds,
H(x) – stands for percentage of cloudiness of high clouds,
AvgWind(x) – stands for average wind speed,
WindMax – value is 20 km/h as authoritary set maximum wind speed, which still will not degrade the PV system.

4.3. Fuzzy rule module

The concept of a Fuzzy Logic Controller (FLC) was introduced in [7] and brought the idea of a form control algorithm as a set of logical rules presented in the following form [8]:

IF x AND y THEN z.

In this paper, the Mamdani FLC has been applied. It can be described as a combination of four sequential steps applied in order to achieve the desired results [8]:

– fuzzification,
– rule evaluation,
– aggregation of rule outputs,
– defuzzification.

To implement the fuzzy controller, there is no need to have its model. The whole process of creation is based on defining the rules on how it should react (rules in the form of conditional statements) [5]. The fuzzy controller has been implemented in the MATLAB environment with the use of Fuzzy Logic Toolbox, which allows us to setup all characteristics for the controller [6]: gaussian membership functions, fuzzy logic rules, defuzzification method.

Both steering values (normalized wind speed and normalized cloudiness) need to have defined membership functions for their fuzzy states. For cloudiness, four states of intensity can be isolated:

– lack of clouds (sunny day),
– weak clouds,
– transparent sky cover,
– overcast.

Membership function for cloudiness is shown in Figure 3.

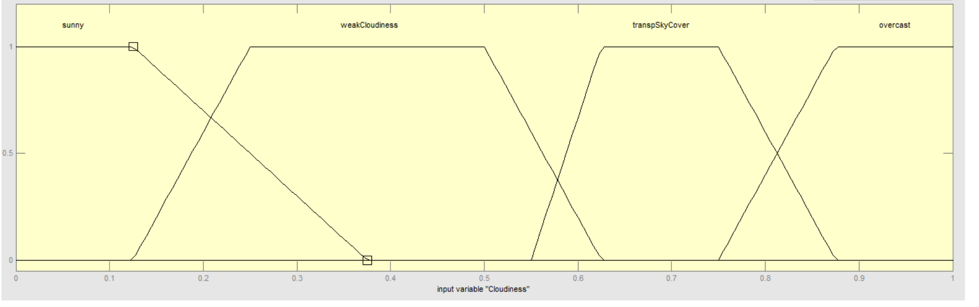

Fig. 3. Cloudiness membership function

For wind speed, three states of intensity can be isolated:

– weak,
– medium,
– strong.

The membership function for wind speed is shown in Figure 4.

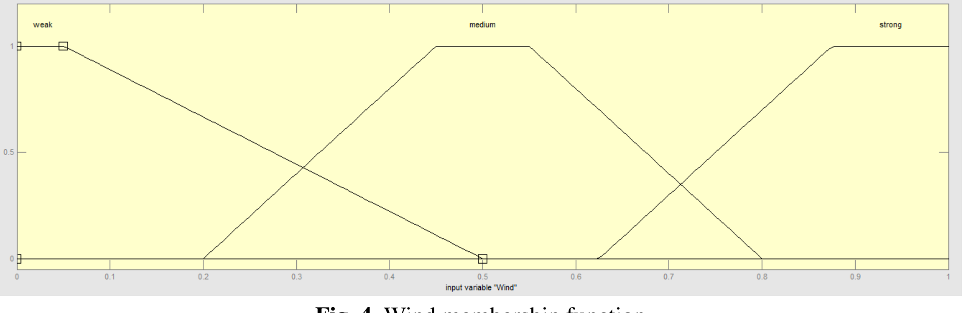

Fig. 4. Wind membership function

From the aforementioned, the storm algorithm triggering is bound only to wind speed, so it does not take part in specifying the membership function for the algorithms. The membership function for control is shown in Figure 5.

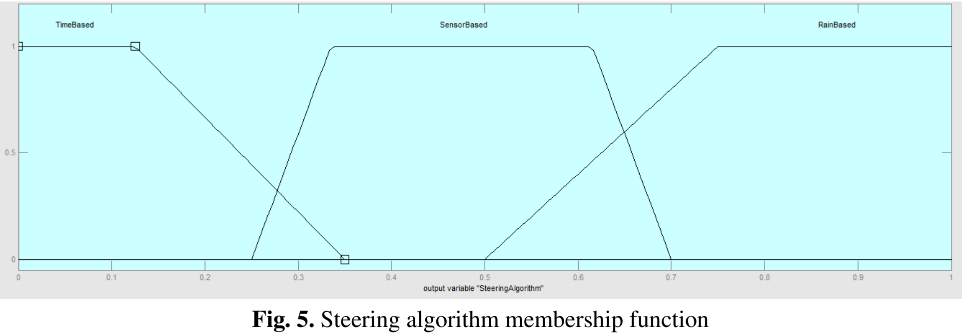

Fig. 5. Steering algorithm membership function

As mentioned earlier, fuzzy rules are one part of a fuzzy controller. The rules used in this paper are given in Table 1.

Table 1
Fuzzy rules

No.	Wind	AND	Cloudiness	Algorithm
1	Medium	AND	Sunny	Time based
2	Medium	AND	Weak	Sensor based
3	Medium	AND	Transparent cover	Sensor based
4	Medium	AND	Overcast	Rain
5	Weak	AND	Sunny	Time based
6	Weak	AND	Weak	Time based
7	Weak	AND	Transparent cover	Rain
8	Weak	AND	Overcast	Rain
9	Strong	–	–	Storm

The time-based algorithm has been indicated as the most suitable one in Rules 1, 5, and 6. This type of algorithm has been chosen due to a cloudiness factor not being higher than the "Weak" value. The wind factor was also never higher than "Medium," which can indicate that the weather conditions are good enough to proceed with the time-based algorithm (which is natural for PV systems).

The sensor-based algorithm has been indicated as the most suitable one in Rules 2 and 3. This type of algorithm has been chosen due to the "Medium" value of the wind and cloudiness factors not in the subset of extreme values ("Overcast," "Sunny"). The sensor-based algorithm is applied when weather conditions cannot be specified as conductive or unfavorable. In these cases, it is suggested to use the sensor-based algorithm in order to provide most accurate steering values.

The rain algorithm has been indicated as the most suitable one in Rules 4, 7, and 8. In the case of Rule 7, the rain algorithm has been chosen because of the "Weak" value of the wind factor – there is no strict indicator to use the sensor-based algorithm in order to reorient the PV system to commit potential danger to the physical elements of the system. In the case of Rules 4 and 8, the rain algorithm has been chosen due to the "Overcast" value of the cloudiness factor.

The defuzzed value is mapped into one of the three aforementioned algorithms with the use of the conditional expressions presented below:

- IF defuzzed value in [0, 0.3] THEN *"Time-based"* algorithm is implemented,
- IF defuzzed value in (0.3, 0.7] THEN *"Sensor-based"* algorithm is implemented,
- IF defuzzed value in (0.7, 1] THEN *"Rain"* algorithm is implemented,
- IF normalized wind value in [0.8, 1] THEN *"Storm"* algorithm is implemented.

5. Example of work

In this section, the exemplary work of the proposed solution is given.

5.1. Input and output data of system

Figure 6 presents the weather forecast with a length of 60 h, which was used as the example input of the described solution.

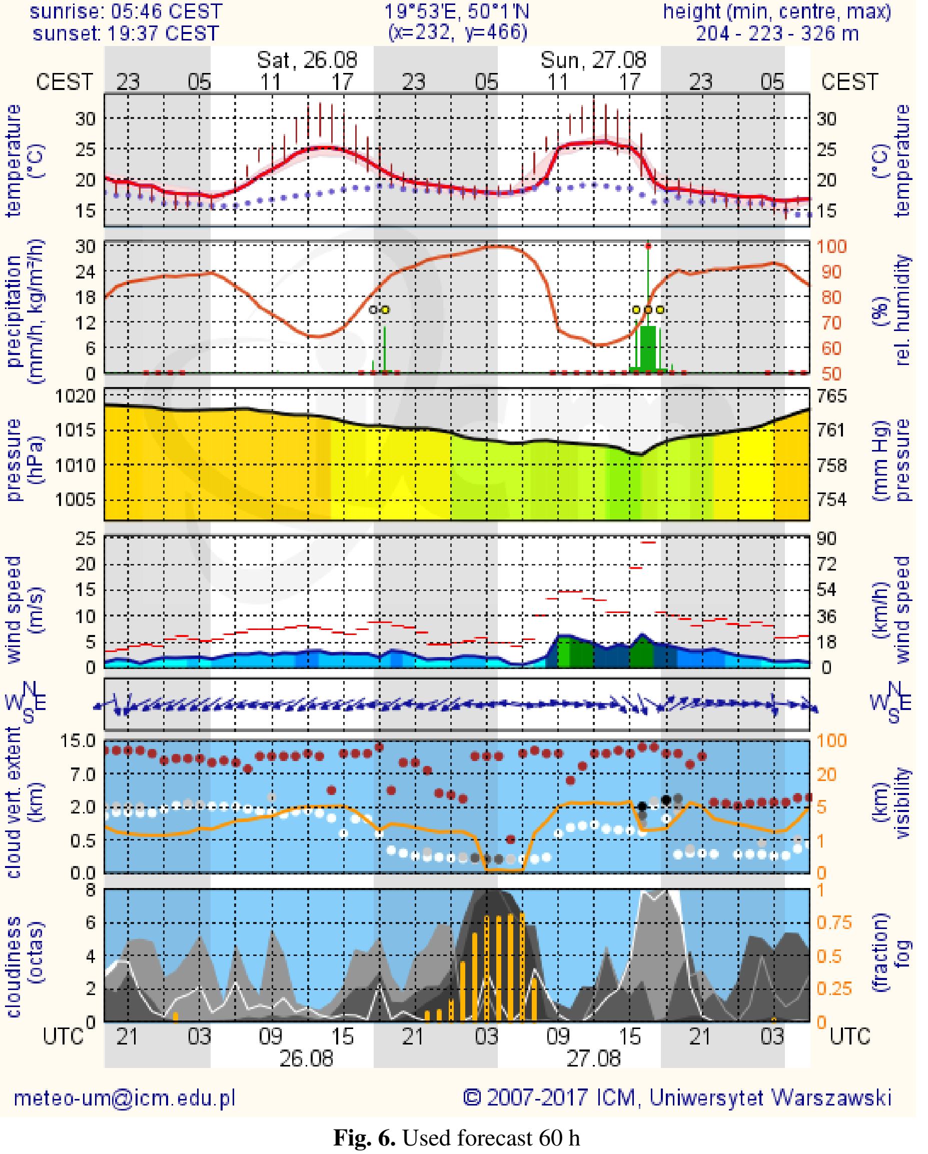

Fig. 6. Used forecast 60 h

Results of the work of the proposed control algorithm are given in Table 2.

Table 2
Results of work

Timestamp	Wind	Cloudiness	Deffuzed value	Algorithm
25-Aug-2017 18:08:44	0.091	0.2416	0.14257	time
25-Aug-2017 19:01:08	0.0985	0.2523	0.14368	time
25-Aug-2017 20:02:16	0.072	0.37245	0.13729	time
25-Aug-2017 21:03:24	0.072	0.2756	0.14617	time
25-Aug-2017 22:04:32	0.071	0.22626	0.14097	time
25-Aug-2017 23:05:40	0.0775	0.12177	0.13092	time
26-Aug-2017 00:06:48	0.069	0.13452	0.13207	time
26-Aug-2017 01:07:56	0.039	0.16352	0.13477	time
26-Aug-2017 02:09:04	0.1165	0.19227	0.13755	time
26-Aug-2017 03:01:28	0.1165	0.19925	0.13826	time
26-Aug-2017 04:02:36	0.1165	0.11923	0.1307	time
26-Aug-2017 05:03:44	0.119	0.2155	0.13988	time
26-Aug-2017 06:04:52	0.1165	0.1705	0.13543	time
26-Aug-2017 07:06:00	0.1225	0.14175	0.13274	time
26-Aug-2017 08:07:08	0.1765	0.24425	0.24548	time
26-Aug-2017 09:08:16	0.1775	0.2155	0.18103	time
26-Aug-2017 10:00:40	0.1775	0.1385	0.13299	time
26-Aug-2017 11:01:48	0.1775	0.11283	0.13299	time
26-Aug-2017 12:02:56	0.1775	0.1032	0.13299	time
26-Aug-2017 13:04:04	0.2105	0.12242	0.13754	time
26-Aug-2017 14:05:12	0.241	0.19798	0.13813	time
26-Aug-2017 15:06:20	0.241	0.3221	0.338	sensor
26-Aug-2017 16:07:28	0.235	0.34875	0.34173	sensor
26-Aug-2017 16:59:52	0.2015	0.40935	0.3272	sensor
26-Aug-2017 18:01:00	0.2015	0.3156	0.33836	sensor
26-Aug-2017 19:02:08	0.2	0.2182	0.1879	time
26-Aug-2017 20:03:16	0.166	0.2719	0.29298	time
26-Aug-2017 21:04:24	0.2	0.355	0.33443	sensor
26-Aug-2017 22:05:32	0.1945	0.39545	0.31685	sensor

Table 2 (cont.)

26-Aug-2017 22:57:56	0.2	0.44785	0.32508	sensor
26-Aug-2017 23:59:04	0.1435	0.45095	0.19949	time
27-Aug-2017 01:00:12	0.0945	0.75125	0.16164	time
27-Aug-2017 02:01:20	0.1	0.85135	0.5	sensor
27-Aug-2017 03:02:28	0.103	0.85135	0.5	sensor
27-Aug-2017 04:03:36	0.1215	0.1	0.12902	time
27-Aug-2017 05:04:44	0.1215	0.1	0.12902	time
27-Aug-2017 06:05:52	0.122	0.1	0.12902	time
27-Aug-2017 06:58:16	0.0445	0.425	0.12859	time
27-Aug-2017 07:59:24	0.024	0.17475	0.13584	time
27-Aug-2017 09:00:32	0.15	0.14999	0.13349	time
27-Aug-2017 10:01:40	0.251	0.14999	0.13349	time
27-Aug-2017 11:02:48	0.3005	0.2417	0.24047	time
27-Aug-2017 12:03:56	0.3005	0.21635	0.18321	time
27-Aug-2017 13:05:04	0.3005	0.3665	0.39411	sensor
27-Aug-2017 14:06:12	0.2555	0.23325	0.22306	time
27-Aug-2017 14:58:36	0.249	0.30585	0.33725	sensor
27-Aug-2017 15:59:44	0.249	0.464	0.3813	sensor
27-Aug-2017 17:00:52	0.249	0.33725	0.34406	sensor
27-Aug-2017 18:02:00	0.3435	0.334	0.36632	sensor
27-Aug-2017 19:03:08	0.35	0.46365	0.45171	sensor
27-Aug-2017 20:04:16	0.25	0.49375	0.38224	sensor
27-Aug-2017 21:05:24	0.2445	0.19882	0.13821	time
27-Aug-2017 22:06:32	0.2405	0.2367	0.23032	time
27-Aug-2017 22:58:56	0.233	0.1951	0.13783	time
28-Aug-2017 00:00:04	0.233	0.2783	0.30235	sensor
28-Aug-2017 01:01:12	0.233	0.4863	0.36541	sensor
28-Aug-2017 02:02:20	0.1985	0.51165	0.32293	sensor
28-Aug-2017 03:03:28	0.1985	0.45315	0.32293	sensor
28-Aug-2017 04:04:36	0.1985	0.5201	0.32293	sensor
28-Aug-2017 05:05:44	0.1205	0.5082	0.12493	time
28-Aug-2017 05:58:08	0.0985	0.43345	0.12732	time

A graphical representation of the data included in Table 2 is presented in Figure 7.

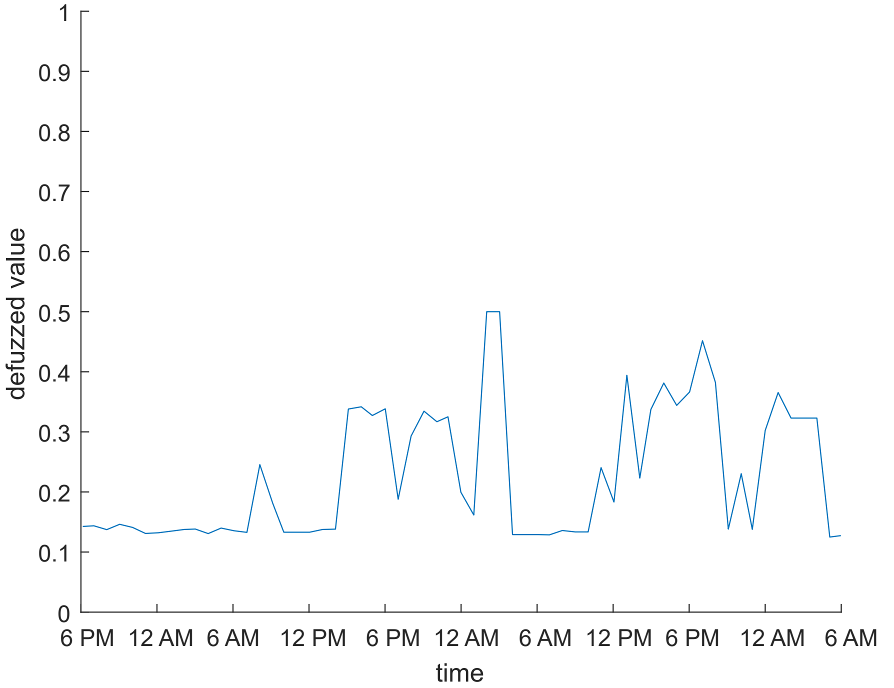

Fig. 7. Graphical representation of results

6. Concluding remarks

As can be observed, the timestamps where the system indicated the sensor algorithm are strongly correlated with the overcast intensity.

Output of the aforementioned system is only the first step into the complex analysis of the weather forecast. Despite the strong overcast conditions that were visually obvious to the human eye, the described system was not able to clearly indicate the storm algorithm but "only" the sensor-based one. As previously mentioned, the storm algorithm is triggered despite the fuzzy controller results (relying on wind speed).

The proposed solution can be extended in several ways:

- cover more than one source for forecasts,
- define more fuzzy logic rules in order to compute the steering algorithm more accurately,
- test more defuzzification methods than the one described.

The potential energy consumption difference was not presented in this paper. In the future evaluation of this paper, it is strongly recommended to take this indicator into consideration.

When writing this paper, no other method for data retrieval from meteo.pl service was available. Potential further research of the presented matter can obtain data from the recently created API for this purpose (https://api.meteo.pl). However, model UM 60 h presented in this paper is not available in the aforementioned service.

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Sterowanie nadrzędne orientowanymi ogniwami słonecznymi z wykorzystaniem prognoz pogody

Streszczenie: Artykuł ten jest poświęcony tematyce opracowania sterowania nadrzędnego ogniw słonecznych, z wykorzystaniem prognoz pogody. Przedstawione w nim rozwiązanie korzysta z podstaw logiki rozmytej, aby zwiększyć wydajność energetyczną ogniw solarnych. W odróżnieniu od większośći prac o podobnej tematyce, wnioskowanie rozmyte służy przetworzeniu danych numerycznych uzyskanych z prognozy pogody. Wszystkie komponenty potrzebne do odtworzenia rozwiązania zostały opisane w artykule.

Słowa kluczowe: *ogniwo słoneczne, logika rozmyta, prognoza pogody, sterowanie nadrzędne, sztuczna inteligencja*