A Fuzzy Model for Controlling an on-grid LED Lamp with a Battery Bank, Powered by Renewable Energy

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Abstract. A model for controlling power and energy flow in an outdoor LED lamp was developed. The lamp was powered by various sources: the power grid, battery bank, photovoltaic panels and a wind turbine. A set of fuzzy control rules was developed based on the defined direction of power flow. The input variables in the control system were battery charge levels, time of day (night), insolation and wind (power generated by a wind turbine). The direction of power (electricity) flow was the output variable. Linguistic variables (distribution of terms) and defuzzification methods were adapted for selected variables. In the produced fuzzy model, system response spaces were verified based on the operation of the control system and the adopted assumption. The resulting fuzzy model adequately meets assumptions and can be used to control power flow in an outdoor LED lamp.

Keywords: fuzzy logic, outdoor LED lamp, energy storage, on-grid systems, control system, renewable energy sources

1 Introduction

Fuzzy logic systems can be effectively used to control non-linear processes [1], [2], [3], [4], including simple control systems in household appliances, as well as more complex systems for image control, traffic control and metro train control [5], [6]. Fuzzy logic systems for controlling various processes have numerous industrial applications, including in wind farms [7], [8], [9] and hydraulic control systems of forging machines [10]. Artificial intelligence and fuzzy logic methods are also applied in environmental protection [11], [12] and composting [13], [14]. A fuzzy model of the composting process has been developed [15]. Systems that rely on fuzzy logic are frequently used in combination with adaptive neuro-fuzzy inference systems (ANIFS) [16].

Fuzzy control systems have the following characteristics:

- they can be used to describe highly complex non-linear systems, in particular when conventional (analytical) descriptions are too complex or impossible;

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- the system/model can be described with the use of natural language expressions based on “expert” knowledge, and the relationships between input and output data can be analyzed to facilitate understanding of the model;
- they can be used to develop hybrid control systems (fuzzy and conventional);
- similarly to artificial neural networks, they are resistant to incomplete (imprecise) data sets and can be used for parallel computing.

2 Basic assumptions of power flow control

A fuzzy model of a power flow control system in an outdoor LED lamp was developed (Fig. 1). The control system was designed based on the following assumptions:
- the LED lamp operates at night (when it is dark);
- the lamp is powered by a wind turbine when wind conditions are adequate;
- the lamp is powered by the battery bank when wind conditions are not adequate and when the battery bank is charged;
- the lamp is powered by the grid when wind conditions are not adequate and when the battery bank is empty;
- the lamp does not operate during the day;
- the battery bank is charged when it is empty and when power is available from PV panels or the wind turbine;
- when the batter is charged and power is available from PV panels or the wind turbine, excess electricity is fed to the grid.

The input variables in the control system are: battery charge level, time of day (night), insolation and wind conditions (power generated by the wind turbine). The output variable is the direction of power (electricity) flow to the battery bank, the grid or the LED lamp. Information about the time of day and insolation is provided by a solar radiation sensor, information about battery charge levels – by the charge controller, and information about the output of the wind turbine – by a sensor in the wind turbine generator (Fig. 1).

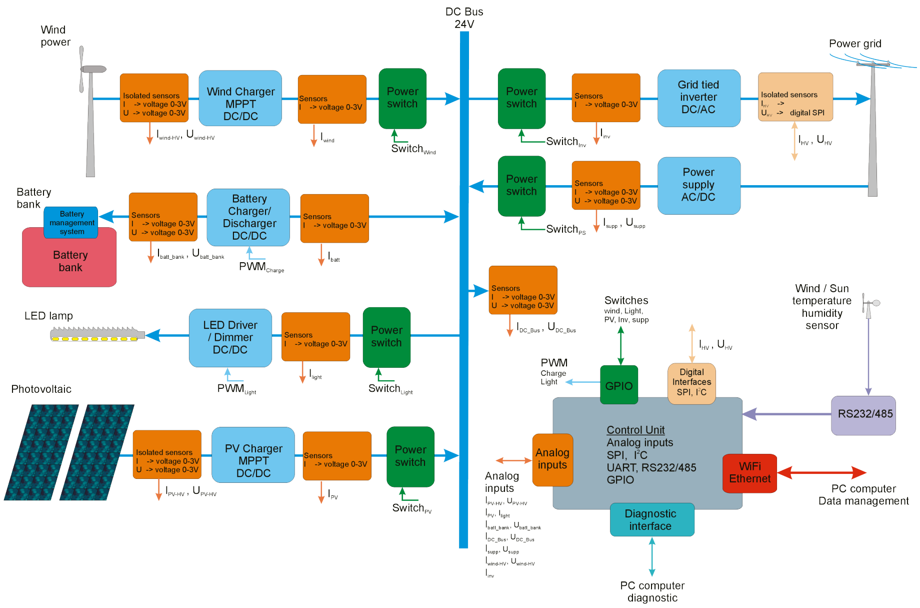

Fig. 1. Connection diagram and the measured parameters in the LED lamp, battery bank, renewable energy sources and the power grid.

3 Fuzzy model

A fuzzy model was developed based on the described assumptions in the LabVIEW program. The distribution of input variable "Wind" is presented in Figure 2.

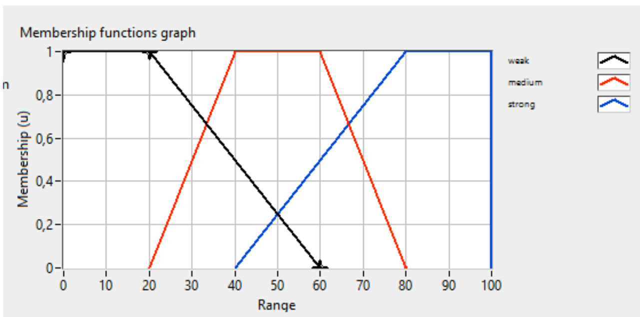

Fig. 2. Distribution of fuzzy terms for input variable "wind".

Twenty-four inference rules were developed (connective: AND (Minimum); implication: Minimum). Initially, there were 36 rules (4 input variables, 2 two-term variables and 2 three-term variables), but since "insolation" coupled with "time of day” can only assume “low” values, 2x6 rules were eliminated. Selected inference rules are presented in Table 1.

Table 1. Selected inference rules

No.	Rules
1	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'night' AND 'Insolation' IS 'low' AND 'Wind' IS 'weak' THEN 'grid' IS 'FROM' ALSO 'LED Lamp' IS 'ON' ALSO 'Battery charging' IS 'OFF'
2	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'night' AND 'Insolation' IS 'low' AND 'Wind' IS 'medium' THEN 'grid' IS 'NOTHING' ALSO 'LED Lamp' IS 'ON' ALSO 'Battery charging' IS 'OFF'
3	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'night' AND 'Insolation' IS 'low' AND 'Wind' IS 'strong' THEN 'grid' IS 'NOTHING' ALSO 'LED Lamp' IS 'ON' ALSO 'Battery charging' IS 'ON'
4	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'day' AND 'Insolation' IS 'low' AND 'Wind' IS 'weak' THEN 'grid' IS 'NOTHING' ALSO 'LED Lamp' IS 'OFF' ALSO 'Battery charging' IS 'OFF'
5	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'day' AND 'Insolation' IS 'low' AND 'Wind' IS 'medium' THEN 'grid' IS 'NOTHING' ALSO 'LED Lamp' IS 'OFF' ALSO 'Battery charging' IS 'ON'
6	IF 'Battery charge level' IS 'Empty' AND 'Time of day' IS 'day' AND 'Insolation' IS 'low' AND 'Wind' IS 'strong' THEN 'grid' IS 'NOTHING' ALSO 'LED Lamp' IS 'OFF' ALSO 'Battery charging' IS 'ON'

The defuzzification method was the Center of Maximum. The value of the output variable was calculated based on the below formula (1):

$$y = \frac{y_1\mu_1 + y_2\mu_2 + \cdots + y_n\mu_n}{\mu_1 + \mu_2 + \cdots + \mu_n} \tag{1}$$

where:
y – value of the output variable;
y_n – input value of function “n”
μ_n – membership value of function “n” for y_n – do

The modeled (control system) response spaces are presented in Figures 3 and 4.

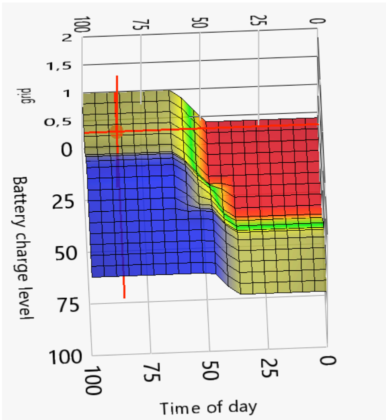

Fig. 3. Response of the control system – power fed to the grid depending on the time of day and battery charge level.

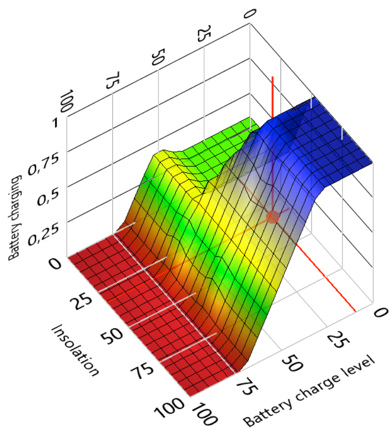

Fig 4. Response of the control system – battery charging depending on insolation and battery charge level.

A detailed analysis of the above figure drawings indicates that at night (when time of day ranges from 0 to 50) when the battery bank is empty (0 to 30/70), the system is powered by the grid (Fig. 3), and when the battery charge level is low and insolation is high, the battery bank is charged (Fig. 4). An analysis of response spaces indicates that the model well fits the data.

4 Conclusions

The proposed control system has the following advantages:

- the operation of the power flow control system can be described with linguistic expressions (input and output variable terms) regardless of the hardware platform, which facilitates the development of inference rules;
- the operation of the power flow control system can be verified based on response space diagrams without the need to implement the algorithm in a real object;
- the power flow control system can be easily modified by introducing changes to the fuzzy model without modifying the physical system (sensors and switches in the power controller, etc.). The modifications can be implemented by entering the new set of fuzzy logic rules into the controller.

The proposed control system operates in accordance with the adopted assumptions.

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