FUZZY RULES FOR OFF-GRID SECURITY SUBSYSTEM

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Abstract. *Stand-alone off-grid power supply system is a necessity for applications when electrical power distribution network is inaccessible. Internal and external subject security aspects should be valued, and the system should be optimized to obtain properly working, never-failing and secure local electrical power supply system. Internal security aspects result from both security concept and used technologies. Internal threats contain fire ignition, flooding, electrical cables melting and other threats arising from intrinsic materials or subsystems characteristics, at standard conditions of use. Additional external aspects include anti-theft protection, breaking doors or windows signaling and countermeasure, weather extremes alert, etc. Both internal and external aspects necessarily induce additional off-grid power system or subject monitoring that might be performed by supervising security subsystem. This paper provides a solution for off-grid security subsystem. It consists from pervasive sensor circuits, fuzzy controlled diagnostics and executive actuators. Cooperated fuzzy logic diagnostic and control device enables to evaluate anticipated threats and dynamically generates the most appropriate decisions about real threat existence that leads to improvement of system protection. Proposed fuzzy rules are particularly discussed in the paper.*

Keywords

Fuzzy logic, off-grid power supply, security subsystem.

1. Introduction

In mountainous European environment, many chalets or cottages as well as telecommunication facilities are powered by off-grid power source. By default, off-grid electrical power supply system consists of electrical power source essential parts: photovoltaic panel subsystem or wind-power plant, fuel or gas generator, or the recuperation equipment. Often, off-grid systems are designed for rare exploited or rare attended single buildings or subjects without security service. Photovoltaic or wind-power based systems can work in unattended mode when nobody keeps the facility, so they can produce electrical power to continuous equipment power supply or to be stored in electrical energy storage subsystem. On the other hand, fuel or gas as well as recuperation generators might loss in unattended mode. Therefore, operating and security subsystems must be continuously monitored, controlled and guarded to achieve the highest energy and feeding efficiency, especially in unattended mode. Electronic security subsystem became an important part of the facility. Not only such system contains electronic alert subsystem to activate local signalization and to send distant information via GSM short message or e-mail in a case of threat, but also it optimizes and controls maximum safety level in cases of other systems failures. The arrangement of several positioned continuously warding pervasive detectors increases the information reliability and improves quality of compound data stream that informs about the guarded facility or subject status. Nevertheless, automated information collection, circuit diagnostics, voting processor and executive actuators control system must be designed to recognize common life events and decrease false alarms [1], [2], [3], [4], [5] and [6].

False alarms are acute problem especially when simple control system is not designed to recognize common life events like atmospheric humidity increase, smoke abatement, cooking, bathing, showering etc., from threat situations, primarily in unattended mode. Thus, several solutions are on demand to decrease false alarms. Here, a precise sensors sensitivity threshold setting is essential. Besides of thresholds setting and fuzzy quantifiers' setup, [11], another solution is attainable: designing of a sophisticated control system well-supplied by data streams of different sensor type's arrangement that can recognize common life events and eliminate mentioned false alarms. For example, to reduce anti-theft false alarms, vibrations induced by vehicle drive might be eliminated using combina-

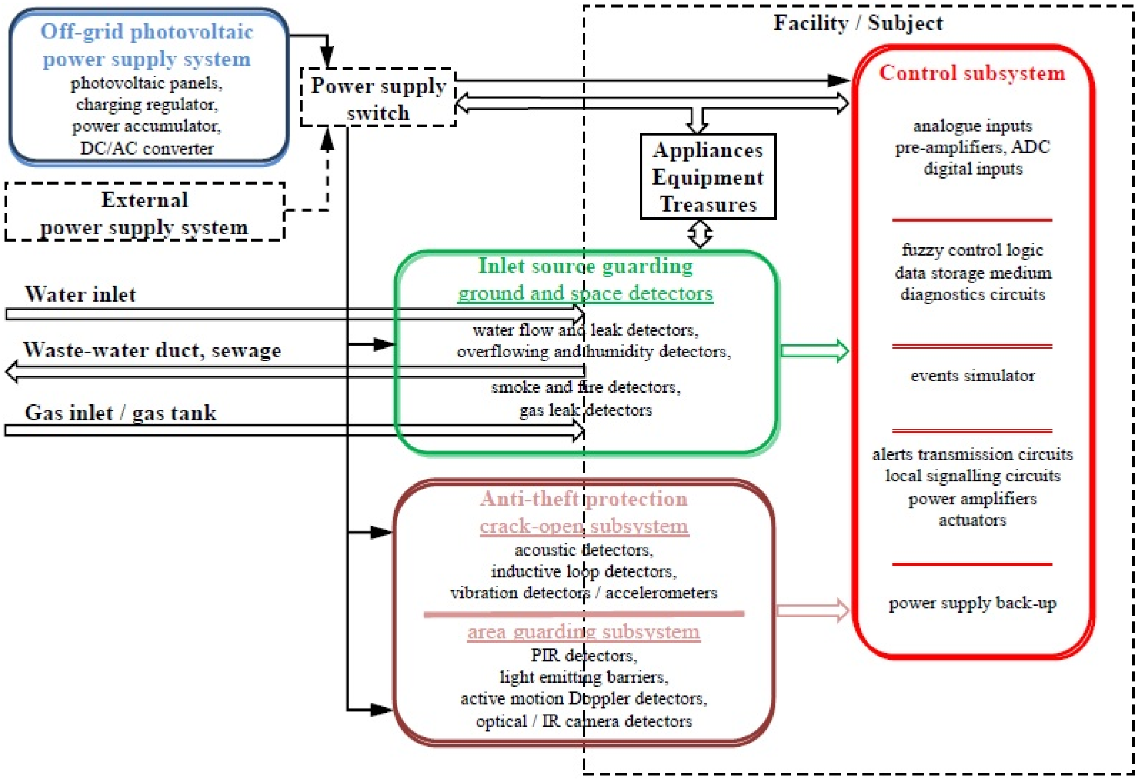


Fig. 1: Block diagram: off-grid photovoltaic power supplied system with integrated security subsystem.

tion of several detectors (e.g. outdoor detectors: subject detectors – namely accelerometers; line detectors like fence, underground or stoppage vibrations detection cables or sensors; area and whole-space detectors – mostly microwave, laser, infrared, or camera detectors), and optimized assessment system [5], [8], [9] and [13]. Such compound data stream coming from sensor arrangement system allows fuzzy logic to increase correct decisions probability (i.e., to activate an alert when threat occurs and, to suppress alert processes when a false alarm occurs).

This paper acts on an idea of fuzzy controlled integrated security subsystem implementation on the off-grid power supply system. The objectives are to achieve appropriate sensor's choose and its sensitivity setup in each of three sensor subsystems (window-breaking subsystem, area guarding subsystem, and inlet sources guarding subsystem), to optimize sensor's data fusion in each of the three sensor subsystems (mainly, membership functions setup for each of the sensors), and to optimize total sensor subsystems setup (mainly, to obtain acceptable sharp common life events recognition and false alarms elimination). Proposed cooperated fuzzy logic control device should evaluate anticipated threats and dynamically generate the most appropriate decisions about real threat existence that leads to improvement of off-grid system protection. To achieve such objectives, control subsystem is designed, optimized and tested in LabVIEW that contains a powerful optimizing compiler to optimize proposed block diagram [12].

2. Integrated Security Subsystem

In proposed off-grid power system, distributed monitoring detectors render combination of time-coherent multi-data stream. An automated control system may be either distributed or centralized architecture designed. Well, the centralized architecture designed in bottom-up approach [3], [8], [13] stands for standard system architecture when compound multi-data stream initializes definite final decision about alert existence and informs user or owner about countermeasures being accepted.

Proposed security subsystem consists of three sensor subsystems and a security control subsystem, Fig. 1. The first sensor subsystem, a window-breaking subsystem, detects windows or glass door breaking by acoustic, vibration detectors and accelerometers, or inductive loops. The second subsystem, an area guarding subsystem, detects warming zones and motion across guarded space, by passive infra-red (PIR) detectors, light emitting barriers, active motion Doppler, optical and infra-red (IR) camera detectors. Both window-breaking and area guarding subsystems constitute the anti-theft protection. The third subsystem, an inlet sources guarding one, detects flow, overflowing, humidity, water or gas leak and a fire using flow, overflowing, smoke, high-sensitive gas, temperature, infra-red (IR) and other detectors. Due to reliable events origin resolution and the most appropriate decision acceptance, the three sensor subsystems are connected to the fuzzy logic based central security control subsystem. Not only configuration of fuzzy rules diminishes false alarms probability, but also it enhances the probability of regular response in events of any threat.

The glass breaking detection is based on sound analysis. Acoustic detector initializes alert in case of gradual sound intensity of specific low frequency (crash) or high frequency (glass break). The high-quality acoustic detectors surely recognize real glass breaking and are utterly resistant against assonance. It is important to place acoustic detectors in windowed or glass door rooms as well as in rooms obtaining glass materials.

Vibration detector can measure and analyze the displacement, linear velocity, or acceleration. Three parameters determine its accuracy and false alarms level: the scale factor (it relates the output signal to an acceleration input force and is linked to sensitivity), the natural frequency (the rate at which the spring-applied mass vibrates forward and backward from equilibrium) and the damping coefficient (the friction that brings the mass to rest). Thus, the vibration detector chose should follow anticipated theft force. An accelerometer measures proper acceleration that is the acceleration experienced relative to freefall. Putting the subject another way, the equivalence principle guarantees the existence of a local inertial frame; thus the accelerometer measures the acceleration relative to that frame. Safe deposit or artwork inclination can be detected by in-plane, two- or three-axis accelerometer. Designer must tradeoff between sensitivity and the maximum measured acceleration.

Inductive loop detector based on Hall effect produces a voltage difference (the Hall voltage) induced across electrical conductor as a result of the magnet and electrical conductor relative movement. By opening of the entrance door or guarded windows, it initiates alert of the security subsystem. Often, it waits doors to be shut down in a short time interval, due to standard life event (notably, unlocking the alarm system by user or owner).

All objects with a temperature above absolute zero emit heat energy in the form of radiation. The PIR detector does not generate or radiate any energy for detection purposes. It works by detecting the different thermal energy irradiated by an unknown object against homogenous thermal background of the guarded subject. Based on such comparison, it can detect the existence of a human body or warm-blooded animal in the room.

Based on the principle of transmitter-to-receiver light beam interruption by a person, animal or thing passing through it, alarm barrier can be used to detect persons passing through doorways, corridors or bordered areas. The transmitter emits a beam of certain optical or infrared frequency band. In the case of rapid light intensity decrease, the output signal of the receiver activates alert. Moreover, it can detect hotspot fire or overheating areas.

An active radio band motion Doppler detector is a common ingredient in security subsystems and automatic door openers. Based on the radio waves transmitting across guarded area or yard and reflection radio waves receiving, it can detect perpendicular cross-zone motion. Depending on the radio wavelength, it can detect the motion even in a hidden space behind the wall.

Another way is to use the optical or IR detectors, different types of optical or IR wavelength cameras. They can operate either in on-line mode when transmitting data via intranet/Internet or, in off-line mode when saving data on data storage medium.

Standard electronic security subsystems include facility or subject protection against fire, smudge or explosives. Smoke detectors like optical smoldering fire detectors or quick ionizing flaming stage fire detectors are used to detect a fire threat. These reliable and high sensitive detectors can measure smoke parts concentration in a room. Moreover, an adaptive control system can distinguish the kind of threat so it can start hotspot area watering until its extinction.

Besides of distance temperature measurement using above described IR sensors, contact temperature sensors exist too. They can measure current subject temperature to get information about its either standard life or hazardous state or activity.

There exist few types of sensors that can detect hazardous gases leak around the gas pipeline, near gas tank, gas cylinder, distribution system joint or gas appliance, or inside of guarded facility. Odorless carbon monoxide, carbon dioxide, flammable gas like natural gas, propane, butane and any other combustible gases can be detected by electrochemical, infrared point, infrared imaging, ultrasonic, semiconductor or polymer holographic sensors. The use of gas leak detector should be a matter-of-course if the gas is used for cooking and heating, especially when it is stored in a rare exploited facilities or subjects without security service. Overloading gas concentration threshold entrapped by high-sensitive gas detector can immediately detect the gas leakage and prevent a serious accident by gas inlet pipework closing and by the security alert initiation.

Water flow, leak, area overflowing and humidity detectors can monitor inlet water consumption or leak, waste-water duct, rain-water routing or diversion, stream water perineocele or drencher, groundwater arising, water evaporation, ship's sweat occurrence around water pipelines, tanks, appliances, or steam occurrence. Overflowing, flow and humidity detectors placed in the technical room, bathroom or kitchen can detect water or steam leakage and prevent serious area flooding by water admission valve closing before hard damages occur.

Since detectors signals or data streams spread over wide range of voltage or current signals (mostly analogue, digital bivalent or multilevel) at different frequency span, digitized signals are required at the input of central fuzzy logic security subsystem. Often, pre-amplifiers and analogue-to-digital converters are designed at the input. Thus, time coherent and parameters utilized signals might be processed to achieve the highest correct decisions probability. Finally, the goal of the security subsystem is achieved by alert transmitting to the user, owner or local actuators thus countermeasures may be undertaken [1], [3].

Often, local signaling via flashing lights or loud buzzer initiation is used to attract the attention of neighbors or to scare away a thief. Here, independent power supply electrical accumulator is the matter of course. It should feed the whole integrated security subsystem until all anti-theft alert activities are done, without its disconnection or circuit's interruption. The power supply and back-up system play an important role in the case of voltage breakdown, too. Therefore, adequate high-quality accumulator is necessary, designed in dependence to system consumption. In this manner, information flow breakdown and uncertainty decrease. When rarely exploited facility is guarded by security subsystem, active simulation of real life events or user presence is used to baffle a housebreaker. Here, control system creates on and off schedules of lights, windows shields, etc.

2.1. Fuzzy Logic

Off-grid security control system must guarantee the overall protection when inlet source guarding detects hazardous event or theft activity occurs. Since some types of detectors operating in guarded area or space can detect both real life and hazardous events, they can co-operate with other detectors to recognize typical events. Profitably, detectors cooperation allows reducing total detectors number, too. However, such concept requires precise nonlinear control logic, especially if detectors operate with different signals types, e.g. bivalent, multilevel digital or analog. Ad hoc fuzzy logic security control subsystem is appropriate for secure recognition of different events types on compound multi-data stream. Its activity recognition algorithm promises significant advantages for accurate activity recognition. First, it can support semantic activity model well because fuzzy operators can be extended easily to check activity semantics. Second, fuzzy approach is more tolerant to environment uncertainty caused by a failure or sensor noise, thanks to its capability of an output activity inference from uncertain sensor observations. Next, since some variability of the facility, guarded subject or person activities are expected, fuzzy events recognition algorithm can tolerate a certain amount of uncertainty. Therefore, fuzzy logic control is suitable for handling intrinsic system uncertainty caused by any specific unexpected activity. Fuzzy control subsystem can recognize hazardous events and initialize definite final decision about alert existence [7].

During fuzzy logic signal processing, typical processes are sequentially executed, Fig. 2. Since sensor dynamics often depend on its construction and local consequence relations, its transduction characteristics have graded character. Similarly, large scale of linguistic expressions describes sensor detectability. Thus, different real life situations split sensor detection range into a few regions. In a fact, a sensor membership function represents degrees of truth or, the statement „activity is detected". The uncertainty about event non-detection would be expressed by an uncertain membership degree. However, some sensors have ramp transduction characteristics while other have nonlinear or step characteristics. Therefore, input membership functions must fit individually for each proposed sensors depending on sensor location (including fluctuations estimation), sensor type, transduction characteristics and its range. Based on precise sensor characteristics knowledge, semantics, experts experience and experts' fuzzy reasoning capabilities, suitable graded membership functions shape are set in the sensor knowledge base (KB), [7], [10], [11]. During fuzzification, crisp current digitized sensors data are associated with either uncertain sets or terms along signal range intervals, thanks to input membership functions stored in sensor knowledge base (KB) extracted during a long-term measure at different conditions. In manner, "blurred" current fuzzy value replaces origin crisp input value, for each sensor. Next, time coherent or precisely shifted sensors fuzzy values are fused into current fuzzy set [14].

Traditionally, supervisory control of systems is based on semantic events knowledge base constituted of real life events, hazardous life events, assumed theft threats, etc. Experienced persons, i.e. experts, implement semantic rules based on their own experience or information obtained from engineering manuals via implication rules or inference rules matrix to be stored in fuzzy

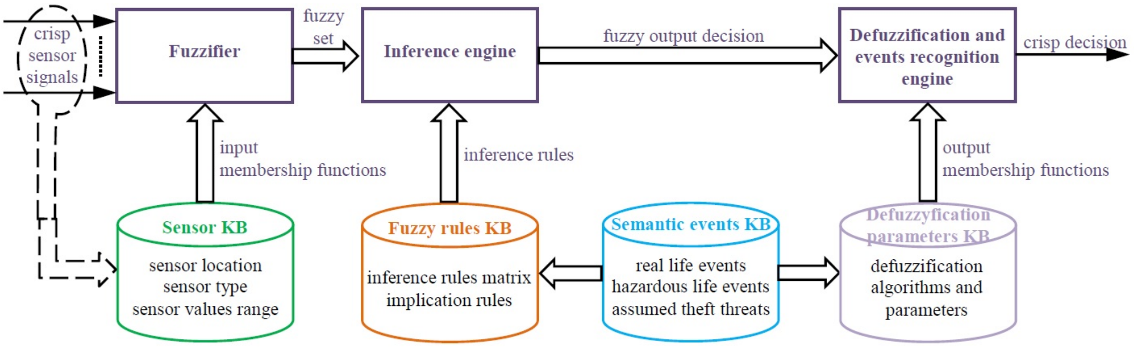


Fig. 2: Central fuzzy control logic security subsystem.

inference rules KB. Similarly, they implement defuzzification rules, algorithms, and parameters to generate output membership functions and to recognize particular events. The expert rules may work acceptably well since they have an abundance of application experience if systems design is relatively simple. For more complex systems, some advanced control schemes should be proposed to achieve better performance. Optimization based on predictive control, dynamic programming, genetic algorithm, simulated annealing and other derivative-free methods are mostly adopted due to nonlinear and discrete characteristics of systems. Considering the large uncertainties, inevitable limitations and simplifications made during the optimization stage, to use such technology without expert validation is unacceptable, anyway. Nevertheless, inference rules are set for particular contexts of real-life situations and invite explanations in terms of various individual semantics. In inference engine, the fuzzy values are compared with given inference rules coming from fuzzy inference rules KB. This comparison creates “blurred” fuzzy output decision that represents degrees of membership functions of fuzzy inference rules, over sensors fuzzy set. Finally, in defuzzification and events recognition engine, fuzzy output decision is defuzzified to obtain definite crisp decision about threat existence, with high accuracy and low false alarms level. The defuzzification process inheres in fuzzy output decision and output membership functions comparison [7], [8], [9], [10], [11] and [13].

In proposed fuzzy control security subsystem, variable signals originate in one of the three sensors subsystem. Let we consider simplified window-breaking subsystem where sound power, sound frequency and vibration detectors voltage signals are combined to detect theft event. In simple non-cooperating case, each of input sensor signals described by its transduction characteristics and distribution function can initiate the alert if the single signal exceeds crisp detection threshold (i.e., τ_{pow}, τ_{freq} or τ_{vib}). In our proposed security subsystem, the τ threshold level follows its statistical distribution: Rayleigh (Eq. 1) for vibrations detector, Gaussian (Eq. 2) for sound power and sound frequency detector:

$$\tau = \mu c_{PFA} = \mu\sqrt{2\sigma^2 \ln\frac{1}{P_{FA}}} = \mu\sigma\sqrt{2\ln\frac{1}{P_{FA}}}, \qquad (1)$$

$$\tau = \mu c_{PFA} = \mu\sigma\frac{\left(\ln\frac{1}{P_{FA}}\right)^{1/\alpha}}{\Gamma\left(1+\frac{1}{\alpha}\right)}, \qquad (2)$$

where μ is signal mean level acquired over the measurement time interval, c_{PFA} is false alarm probability constant notably depending on σ standard deviation and P_{FA} false alarm probability. However, other statistical distributions may be more suitable for other sensors transduction characteristic.

By noiseless slow theft case (furthermore, followed by power supply line interruption) serious system failure may occur. Notwithstanding that under-threshold detection combined from the three sensors increases detection probability for heretofore unnoticed theft event and, decreases total P_{FA}. Such combination requires precise parameters setting. For the three V voltage signals, we calculate their crisp statistical μ mean levels and σ standard deviations in any i-th of n-timing points (measurement cooperation interval):

$$\mu_{pow} = \frac{\sum_{i=1}^{n} V_{powi}}{n}, \qquad (3)$$

$$\sigma_{pow} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_{powi}-\mu_{pow}\right)^2}{n}}, \qquad (4)$$

$$\mu_{freq} = \frac{\sum_{i=1}^{n} V_{freqi}}{n}, \qquad (5)$$

$$\sigma_{freq} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_{freqi}-\mu_{freq}\right)^2}{n}}, \qquad (6)$$

$$\mu_{vib} = \frac{\sum_{i=1}^{n} V_{vibi}}{n}, \qquad (7)$$

$$\sigma_{vib} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_{vibi}-\mu_{vib}\right)^2}{n}}. \qquad (8)$$

Representativeness of such crisp set:

$$\left\{\mu_{pow}, \sigma_{pow}, \mu_{freq}, \sigma_{freq}, \mu_{vib}, \sigma_{vib}\right\}, \qquad (9)$$

inheres in statistical data selection.

However, specific bilateral as well as multilateral relationships exist among these statistical moments. To get cross-relationships and their trends, crisp set must be redefined to "blurred" membership function, a group of interval numbers representing appropriate interval signal ranges. Fuzzification inheres in parametric or linear multiplication (e.g., using standard deviation). We bring an example of simple triangular $\mu(\ldots)$ membership functions for sound power detector, for both mean Eq. 10 and standard deviation Eq. 11. The three level semantics (low, middle and upper bounds) is used.

$$\mu\left(\mu_{pow}\left(V_{powi},\underline{\mu_{powi}},\mu_{powi},\overline{\mu_{powi}}\right)\right) = \\ = \begin{cases} 0 & \underline{\text{if } \ \mu_{powi}} > V_{powi} > \overline{\mu_{powi}} \\ \frac{V_{powi}-\underline{\mu_{powi}}}{\mu_{powi}-\underline{\mu_{powi}}} & \underline{\text{if } \ \mu_{powi}} \leq V_{powi} \leq \overline{\mu_{powi}} \\ \frac{\overline{\mu_{powi}}-V_{powi}}{\overline{\mu_{powi}}-\mu_{powi}} & \text{if } \ \mu_{powi} \leq V_{powi} \leq \overline{\mu_{powi}} \\ 1 & \text{if } \ V_{powi} = \mu_{powi} \end{cases}, \quad (10)$$

$$\mu\left(\sigma_{pow}\left(V_{powi},\underline{\sigma_{powi}},\sigma_{powi},\overline{\sigma_{powi}}\right)\right) = \\ = \begin{cases} 0 & \underline{\text{if } \ \sigma_{powi}} > V_{powi} > \overline{\sigma_{powi}} \\ \frac{V_{powi}-\underline{\sigma_{powi}}}{\sigma_{powi}-\underline{\sigma_{powi}}} & \underline{\text{if } \ \sigma_{powi}} \leq V_{powi} \leq \overline{\sigma_{powi}} \\ \frac{\overline{\sigma_{powi}}-V_{powi}}{\overline{\sigma_{powi}}-\sigma_{powi}} & \text{if } \ \sigma_{powi} \leq V_{powi} \leq \overline{\sigma_{powi}} \\ 1 & \text{if } \ V_{powi} = \sigma_{powi} \end{cases}. \quad (11)$$

However, not the only simple triangular shaped functions are used to fulfill a membership function. To optimize fuzzy values, they can be trapezoidal, Pi-type, bell-type Gaussian, sigmoidal, etc., even mixed. In this step, we used LabVIEW optimizing compiler to obtain more suitable cross-relationships among multilateral detector's statistical moments, too. Even bounds may change by intervals precising or atomization etc., fuzzy intervals must overlay whole signal range, Eq. 12, Eq. 13:

$$\mu_{pow} \subseteq \\ \subseteq \sup V_1^x \mu_{powi}\left(V_{powi},\underline{\mu_{powi}},\mu_{powi},\overline{\mu_{powi}}\right). \quad (12)$$

$$\sigma_{pow} \subseteq \\ \subseteq \sup V_1^x \sigma_{powi}\left(V_{powi},\underline{\sigma_{powi}},\sigma_{powi},\overline{\sigma_{powi}}\right). \quad (13)$$

In next step, we compared fuzzy values to inference rules in fuzzy inference engine. Fuzzy inference process involves fuzzy logical operations (AND, OR, NOT), and implication IF-THEN rules use over all of the membership functions pieces. Thus, combined window-breaking fuzzy subsystem implies $H(.)$ fuzzy decision under hypotheses H_1 event existence or H_0 event non-existence, Eq. 14.

Using Lukasiewicz three-valued logic and operations (implication, negation, equivalence, weak conjunction, strong conjunction, weak disjunction, strong disjunction and propositional constants), parameters relationships reveal. These new fuzzy relationships obtained via fuzzy composition are intrinsically interconnected by time and energetic signals coincidence in the subsystem (nay, coherence). Thus, we obtained R_{sub} subsystem fuzzy decision by current event residual voltage to decision membership function comparison, Eq. 15. Such relationship statement leads to either $Int(H_1)$ intentional expression, Eq. 16, and rather $Ext(H_1)$ extensional expression, Eq. 17. To solve valid affiliation of this extension to either positive or negative decision, we used $L(H_1)$ horizon level, Eq. 18. To obtain definite crisp decision, defuzzification process must follow principles of defuzzification method. Here we used COA (Center Of Area) method given by Eq. 19.

Similarly to sound power detector, we expressed membership functions for frequency and vibration sensors parameters. Combination of such membership functions constitutes the window breaking subsystem fuzzy set [14].

Similarly to window-breaking subsystem, we applied the above methods and processes for both area guarding and inlet sources subsystems in proposed off-grid security subsystem. Combination of the three subsystems membership functions constitutes the security subsystem fuzzy set [14].

For the two anti-theft protection subsystems (window-breaking and area guarding) operating in the same area, we combined its signals by logic operations. Thus, we used detector's signals simultaneously entered via different subsystems to solve different threats parallel. It is expected the inlet sources sensor subsystem operates separately; anyway, there can occur a situation when a thief not only initiates the theft alert but also initiates inlet sources alert by use of fire, water sources etc. Thus, we used additional data fusion.

2.2. Fuzzy Control Design

Graphical programming software platform LabVIEW has been used to design proposed fuzzy control logic security subsystem. To advantage, it allows designing of any measurement equipment via software modular system, including virtual tools support. It is designed as a flexible development software environment supported by hardware modules, a set of efficient universal or specialized input-output devices. They can measure signals, collect and process measured data. For interactive fuzzy control designing, testing and modifying,

$$H\left(\right)=\begin{cases}
0 & \begin{array}{l}\mu_I\left(H_{0\,pow}\right)=\left\{\tau_{pow},V_{i\,pow},\mu_I\left(\tau_{pow}\right)\geq\mu_I\left(V_{i\,pow}\right)\right\}\equiv\\ \equiv\mu\left(\frac{\tau_{pow}-V_{i\,pow}}{\tau_{pow}-V_{\min pow}}\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,freq}\right)=\left\{\tau_{freq},V_{i\,freq},\mu_I\left(\tau_{freq}\right)\geq\mu_I\left(V_{i\,freq}\right)\right\}\equiv\\ \equiv\mu\left(\frac{\tau_{freq}-V_{i\,freq}}{\tau_{freq}-V_{\min freq}}\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,vib}\right)=\left\{\tau_{vib},V_{i\,vib},\mu_I\left(\tau_{vib}\right)\geq\mu_I\left(V_{i\,vib}\right)\right\}\equiv\\ \equiv\mu\left(\frac{\tau_{vib}-V_{i\,vib}}{\tau_{vib}-V_{\min vib}}\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,pow,freq}\right)=\left\{\tau_{pow},\tau_{freq},V_{i\,pow},V_{i\,freq},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{freq}\right)\right]\geq\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,freq}\right)\right]\right\}\equiv\\ \equiv\mu\left(\left(\frac{\tau_{pow}-V_{i\,pow}}{\tau_{pow}-V_{\min pow}}\right)\left(\frac{\tau_{freq}-V_{i\,freq}}{\tau_{freq}-V_{\min freq}}\right)\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,pow,vib}\right)=\left\{\tau_{pow},\tau_{vib},V_{i\,pow},V_{i\,vib},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{vib}\right)\right]\geq\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\right\}\equiv\\ \equiv\mu\left(\left(\frac{\tau_{pow}-V_{i\,pow}}{\tau_{pow}-V_{\min pow}}\right)\left(\frac{\tau_{vib}-V_{i\,vib}}{\tau_{vib}-V_{\min vib}}\right)\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,freq,vib}\right)=\left\{\tau_{freq},\tau_{vib},V_{i\,freq},V_{i\,vib},\left[\mu_I\left(\tau_{freq}\right)\cap\mu_I\left(\tau_{vib}\right)\right]\geq\left[\mu_I\left(V_{i\,freq}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\right\}\equiv\\ \equiv\mu\left(\left(\frac{\tau_{freq}-V_{i\,freq}}{\tau_{freq}-V_{\min freq}}\right)\left(\frac{\tau_{vib}-V_{i\,vib}}{\tau_{vib}-V_{\min vib}}\right)\right)\end{array}\\
0 & \begin{array}{l}\mu_I\left(H_{0\,pow,freq,vib}\right)=\tau_{pow},\tau_{freq},\tau_{vib},V_{i\,pow},V_{i\,freq},V_{i\,vib},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{freq}\right)\cap\mu_I\left(\tau_{vib}\right)\right]\geq\\ \geq\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,freq}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\equiv\mu\left(\left(\frac{\tau_{pow}-V_{i\,pow}}{\tau_{pow}-V_{\min pow}}\right)\left(\frac{\tau_{freq}-V_{i\,freq}}{\tau_{freq}-V_{\min freq}}\right)\left(\frac{\tau_{vib}-V_{i\,vib}}{\tau_{vib}-V_{\min vib}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,pow}\right)=\left\{\tau_{pow},V_{i\,pow},\mu_I\left(\tau_{pow}\right)<\mu_I\left(V_{i\,pow}\right)\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,pow}-\tau_{pow}}{V_{\max pow}-\tau_{pow}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{1\,freq}\right)=\left\{\tau_{freq},V_{i\,freq},\mu_I\left(\tau_{freq}\right)<\mu_I\left(V_{i\,freq}\right)\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,freq}-\tau_{freq}}{V_{\max freq}-\tau_{freq}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,vib}\right)=\left\{\tau_{vib},V_{i\,vib},\mu_I\left(\tau_{vib}\right)<\mu_I\left(V_{i\,vib}\right)\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,vib}-\tau_{vib}}{V_{\max vib}-\tau_{vib}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,pow,freq}\right)=\left\{\tau_{pow},\tau_{freq},V_{i\,pow},V_{i\,freq},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{freq}\right)\right]<\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,freq}\right)\right]\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,pow}-\tau_{pow}}{V_{\max pow}-\tau_{pow}}\right)\left(\frac{V_{i\,freq}-\tau_{freq}}{V_{\max freq}-\tau_{freq}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,pow,vib}\right)=\left\{\tau_{pow},\tau_{vib},V_{i\,pow},V_{i\,vib},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{vib}\right)\right]<\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,pow}-\tau_{pow}}{V_{\max pow}-\tau_{pow}}\right)\left(\frac{V_{i\,vib}-\tau_{vib}}{V_{\max vib}-\tau_{vib}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,freq,vib}\right)=\left\{\tau_{freq},\tau_{vib},V_{i\,freq},V_{i\,vib},\left[\mu_I\left(\tau_{freq}\right)\cap\mu_I\left(\tau_{vib}\right)\right]<\left[\mu_I\left(V_{i\,freq}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\right\}\equiv\\ \equiv\mu\left(1-\left(\frac{V_{i\,freq}-\tau_{freq}}{V_{\max freq}-\tau_{freq}}\right)\left(\frac{V_{i\,vib}-\tau_{vib}}{V_{\max vib}-\tau_{vib}}\right)\right)\end{array}\\
1 & \begin{array}{l}\mu_I\left(H_{I\,pow,freq,vib}\right)=\tau_{pow},\tau_{freq},\tau_{vib},V_{i\,pow},V_{i\,freq},V_{i\,vib},\left[\mu_I\left(\tau_{pow}\right)\cap\mu_I\left(\tau_{freq}\right)\cap\mu_I\left(\tau_{vib}\right)\right]<\\ <\left[\mu_I\left(V_{i\,pow}\right)\cap\mu_I\left(V_{i\,freq}\right)\cap\mu_I\left(V_{i\,vib}\right)\right]\equiv\mu\left(1-\left(\frac{V_{i\,pow}-\tau_{pow}}{V_{\max pow}-\tau_{pow}}\right)\left(\frac{V_{i\,freq}-\tau_{freq}}{V_{\max freq}-\tau_{freq}}\right)\left(\frac{V_{i\,vib}-\tau_{vib}}{V_{\max vib}-\tau_{vib}}\right)\right)\end{array}
\end{cases}. \tag{14}$$

$$R_{sub}\left(H_1\right)=\begin{cases}0 & V_{pow\,rez}\circ V_{freq\,rez}\circ V_{vib\,rez}<\tau_{pow}\circ\tau_{freq}\circ\tau_{vib}\\ 1 & V_{pow\,rez}\circ V_{freq\,rez}\circ V_{vib\,rez}\geq\tau_{pow}\circ\tau_{freq}\circ\tau_{vib}\end{cases}. \tag{15}$$

$$Int\left(H_1\right)=\left\{\begin{array}{ll}\dfrac{R_{sub}(H_1)}{f\begin{pmatrix}\mu\left(\mu_{pow}\left(.\right)\circ\sigma_{pow}\left(.\right)\right)\circ\\ \circ\mu\left(\mu_{freq}\left(.\right)\circ\sigma_{freq}\left(.\right)\right)\circ\\ \circ\mu\left(\mu_{vib}\left(.\right)\circ\sigma_{vib}\left(.\right)\right)\end{pmatrix}} & H_1\in\left[0,1\right]\end{array}\right\}. \tag{16}$$

$$Ext_v\left(H_1\right)=\left\{\begin{array}{ll}\frac{V_i\geq R_{sub}\left(H_{0,1}\right)}{v} & v\in V,H_1\in\left[0,1\right]\end{array}\right\}. \tag{17}$$

$$L\left(H_1\right)=\left(1-\frac{V_{pow\,rez}\circ V_{freq\,rez}\circ V_{vib\,rez}}{\tau_{pow}\circ\tau_{freq}\circ\tau_{vib}}\right). \tag{18}$$

$$COA\left(R_{sub}\left(H_1\right)\right)=\frac{\sum_{i=1}^{n}R_{i\,sub}\left(H_1\right)\left(V_{pow\,rez}\circ V_{freq\,rez}\circ V_{vib\,rez}\right)}{\sum_{i=1}^{n}R_{i\,sub}\left(H_1\right)}. \tag{19}$$

interactive Fuzzy System Designer software tools set is available. Created users projects can be run either in simulation or in real mode [12].

LabVIEW graphic user interface application windows allow front panel programming for our off-grid security subsystem, Fig. 3, and block diagram, Fig. 4, utilizing their programmed background connectivity. Front panel graphic programming offers optional preprogrammed terminal controls use. In Fig. 3, our security control subsystem front panel for off-grid security subsystem consists of the three simplified input sensor subsystems described above (window breaking, area guarding and gas leakage & fire guarding subsystems), integrated fuzzy control subsystem and two alert outputs. Terminal controls shape and parameters range setting is necessary to achieve optimal terminal controls characteristics.

The program code is developed using graphical block diagram window, Fig. 4. As there exists background connectivity, block diagram contains same inputs and outputs as the front panel does. Fuzzy control subsystem is distributed into functional blocks; their parameters' setting is necessary to achieve optimal fuzzy signal processing. Signal and data fuzzy processing blocks are interconnected to other blocks to compute required parameters. Necessarily, membership functions must correspond to real behavior of the controlled system. All input and output variables can be chosen and described linguistically.

In Fig. 4, crisp current sensors output values are split into degrees interval functions over sensor's detection range. They are fuzzified thanks to input membership functions stored in sensor knowledge base (they are extracted during a long-term previous measure at different conditions and set by experts). Blurred current fuzzy value replaces origin crisp input value, for each sensor. Then fuzzy values pass to the Multiple-Input Single-Output (MISO) subsystem's circuits. Here, time coherent sensors fuzzy values are fused into current fuzzy set. If any of single sensors signals reaches set threshold, an alert occurs at the subsystem output. To eliminate false alarm occurrence, the thresholds values are set quite high. On the other hand, the subsystem sensors combination often allows simultaneous detection of the same event thus inter-sensor defuzzification rules are set, too. Such approach substantially eliminates false alarms occurrence at the output of subsystem. To get optimized inference rules and defuzzification rules, we used Takagi-Sugeno method in LabVIEW optimizing compiler. Finally, defuzzification process described in the above chapter 2.1 provides for final crisp alert decision.

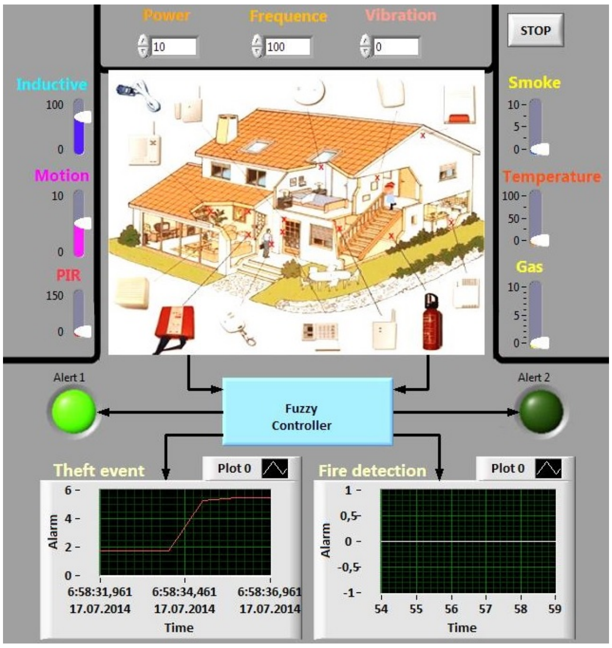


Fig. 3: Off-grid security subsystem front panel.

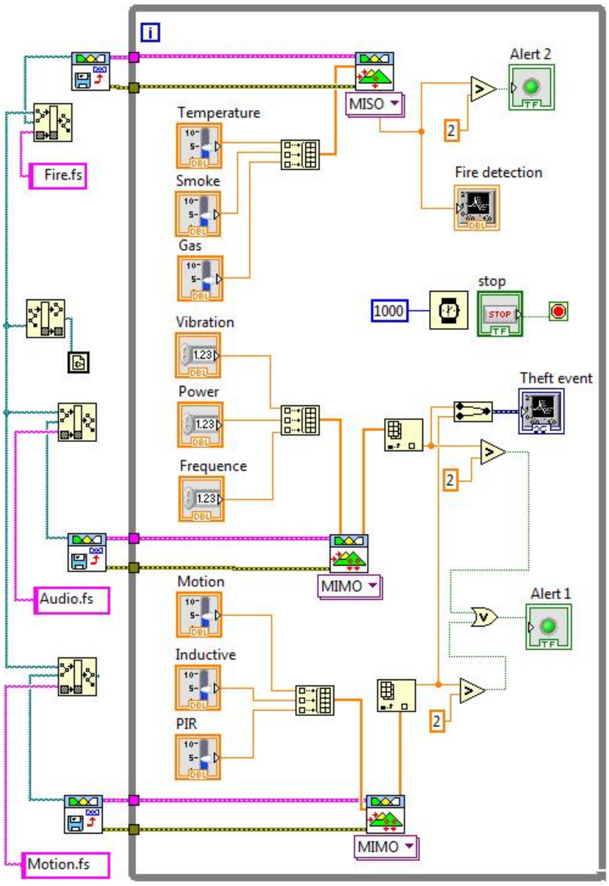


Fig. 4: Fuzzy control block diagram for off-grid security subsystem.

3. Simulation Results and Discussions

Crisp signal parameters measurement, output detector's range, and consecutive input fuzzy membership functions setup are the most important preparation expertise operations exercised for fuzzification process done in our security subsystem. Based on real life events, hazardous life events, and assumed theft events, we precisely set semantic events knowledge base and implied fuzzy inference rules. Similarly, we precisely set defuzzification rules and events recognition algorithms. Finally, we optimized both inference defuzzification rules by Takagi-Sugeno method in LabVIEW optimizing compiler.

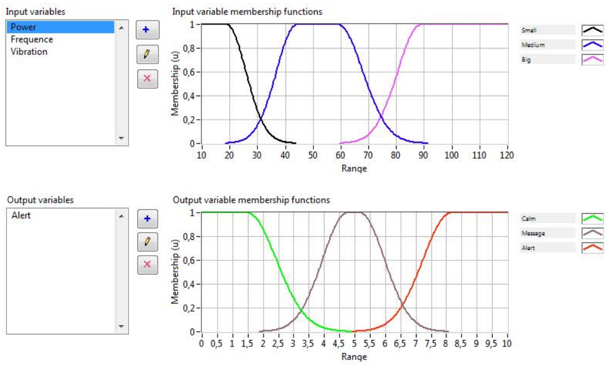
In Fig. 5, an example of window-breaking detection optimized Gaussian input membership function and output membership function (optimized) are shown. Both they are bell-type shaped, depending on real sensor signal probabilistic distribution function and measurement expertise. In the sensor input membership function, interval curves represent low, medium and high detection degree of the hazardous event detected by single operated detector. On the other hand, by output membership function, three intervals represent low, medium and high detection probability of the hazardous event detected by window breaking subsystem detectors combination. If the probability is low, no alert is activated. If the probability is medium or high, a message or an alert is transmitted to the user, owner or local actuators. Here, the output membership function achieves higher detection probability then input membership function of a single detector. It means that even small detection probability growth in next (auxiliary) detector causes total detection uncertainty decrease.

In Fig. 6, our setup example of window-breaking detection fuzzy inference rules setup (expert) is shown (instead of semantic / linguistic rules), by Matlab. For the three detectors exerting three intervals each, we incorporated 27 inference rules that conclude to 27 IF-THEN rules. They are visualized in the Fig. 7. The output decision arising from single detection level of sound power detector at 39.1 dB level (see vertical red line) hardly could initiate an alert. But, since the sound frequency occurs at 1000 Hz that lies at the border of glass breaking narrow frequency bandwidth, its notable contribution of detection level causes combined two-detector probability reliable reveals window-breaking threat as it follows the 16-th inter-sensor inference rule. Thus, the output decision represented by blue colored areas in Alert column is medium short. The thick red line in the floor picture occurred at level 80 % represents alert crisp decision probability. In shown example, no vibration detector contribution is necessary to window-breaking alert activation.

To run fuzzy control model simulation, mandatory fuzzy parameters as well as optional fuzzy processing algorithms must be set first. In proposed security subsystem, we set all of the sensor parameters with respect to their transduction characteristics, via above mentioned methods and principles. After Takagi-Sugeno method using in LabVIEW optimizing compilation to gain all the optimized relationships among fuzzified signal parameters, we tested our model setting in simulation executing mode.

To study the response of fuzzy blocks over input signals range, we visualized paired signals by three-dimensional surface plots. Continuing from previous figures, in Fig. 8 we show our example of inter-sensor alert threshold, by window-breaking acoustic sensor subsystem. The relationship between paired power and frequency sensor is shown. This allows deeper analyzing of the output variable depending on input signals thus presume the alert initiation. In the picture, an alert might be activated either by single-sensor detection or by inter-sensor detection if the signal value oversteps the threshold level (described by the three blunted blue-colored threshold climaxes: the inter-sensor dark-blue one lies backward while other two single-sensor lie at alongside "wings"). There exist two transitory trench-shaped regions between the three blunted climaxes that represent slightly softer double-sensor threshold value, since double-sensor combined signals contribution might cause an alert loss. However, directing to inter-sensor dark-blue climax, the threshold level rises again to achieve the highest possible level 8. As seen in the picture, red lines (they represent current crisp sensors values) slightly overlap the blue alert threshold region by three cross-sections. It means that an alert is activated. In the picture, we obtained also a message regions (described by the three piedmont yellow-colored threshold plateau: the inter-sensor one lies in the middle while other two single-sensor lie alongside), that activate either single-sensor or inter-sensor message transfer. As seen in the picture, red lines considerable overlaps the yellow message threshold region but, no cross-sections are obtained; thus no message is transmitted in the current case. Lastly, there also exist very low red threshold regions representing real life activities or, where the existence of any alert is improbable. As seen in the picture, red lines considerable overlaps the red real life threshold region but, no cross-sections are obtained; thus no real life is detected in the current case.

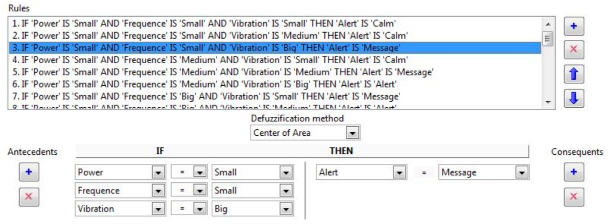
During our experimental work, we adopted different types of membership functions set to real sensor model. For proposed sensors set, bell-type membership functions are the most suitable since they fit sensor transduction characteristics the most. Comparing to tri-



Input variables
Power
Frequence
Vibration

Output variables
Alert

Fig. 5: Visualization of window-breaking detection membership functions.



Rules
1. IF 'Power' IS 'Small' AND 'Frequence' IS 'Small' AND 'Vibration' IS 'Small' THEN 'Alert' IS 'Calm'
2. IF 'Power' IS 'Small' AND 'Frequence' IS 'Small' AND 'Vibration' IS 'Medium' THEN 'Alert' IS 'Calm'
3. IF 'Power' IS 'Small' AND 'Frequence' IS 'Small' AND 'Vibration' IS 'Big' THEN 'Alert' IS 'Message'
4. IF 'Power' IS 'Small' AND 'Frequence' IS 'Medium' AND 'Vibration' IS 'Small' THEN 'Alert' IS 'Calm'
5. IF 'Power' IS 'Small' AND 'Frequence' IS 'Medium' AND 'Vibration' IS 'Medium' THEN 'Alert' IS 'Message'
6. IF 'Power' IS 'Small' AND 'Frequence' IS 'Medium' AND 'Vibration' IS 'Big' THEN 'Alert' IS 'Alert'
7. IF 'Power' IS 'Small' AND 'Frequence' IS 'Big' AND 'Vibration' IS 'Small' THEN 'Alert' IS 'Message'

Defuzzification method: Center of Area

Antecedents — IF
Power = Small
Frequence = Small
Vibration = Big

THEN — Consequents
Alert = Message

Fig. 6: Fuzzy inference rules setup.

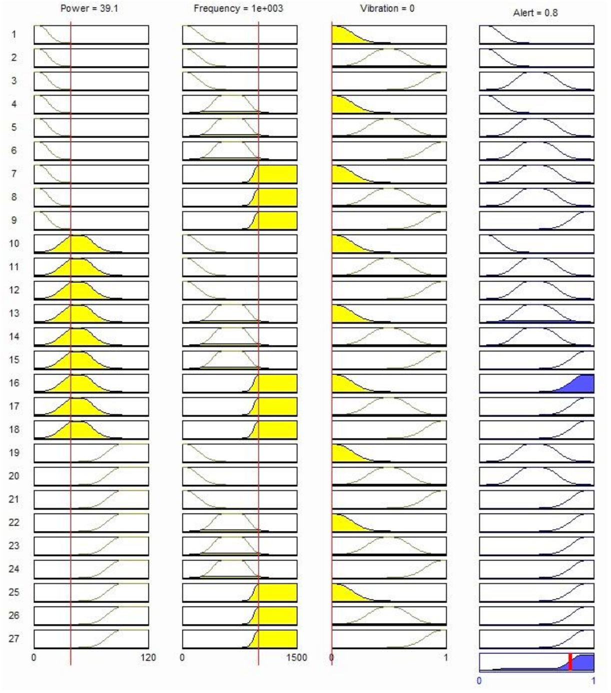
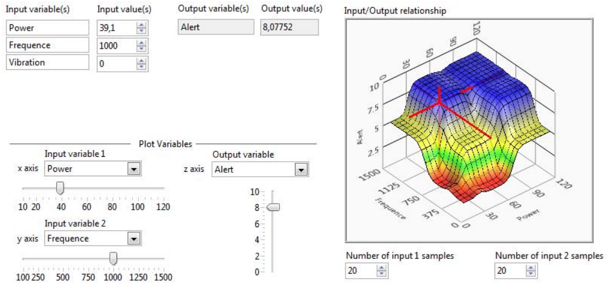


Fig. 7: Visualization of fuzzy inference rules basis.



Input variable(s)	Input value(s)
Power	39,1
Frequence	1000
Vibration	0

Output variable(s)	Output value(s)
Alert	8,07752

Plot Variables
Input variable 1, x axis: Power
Input variable 2, y axis: Frequence
Output variable, z axis: Alert
Number of input 1 samples: 20
Number of input 2 samples: 20

Fig. 8: Sound power sensor to frequency sensor signals relationship.

angle or trapezoidal membership functions, bell-type membership functions achieved the highest smoothness of inter-sensor input and output parameters as well as adequately sharp gaps among the three different crisp decisions required at the output of proposed off-grid security subsystem. To test our expert setup and achieve our goals, we optimized control subsystem by LabVIEW optimizing compiler thus final output functions were obtained. As a result of such computer modeling, LabWIEW optimized membership functions and inference rules were obtained very similar to expert ones.

4. Conclusion

In the article, we presented centralized architecture of fuzzy control subsystem that improves security and system protection of off-grid system. Our multisensory cooperated fuzzy control subsystem simultaneously evaluates three groups of threat and, it dynamically generates the most appropriate crisp decisions about either real life events or two degrees of threat. In proposed security subsystem, desirable sensors were selected to achieve reliable single-sensor or multi-sensor output detection characteristics. During fuzzy control processes, different expert inference rules and output membership functions were used and optimized to obtain the most appropriate fuzzy output decision and crisp output decision, with respect of real life location and with mathematically rigorous optimization support.

The article has presented applicability of fuzzy control system for security improvement for off-grid power supplied facility or subject. As proven in the article, fuzzy logic security control is appropriate for off-grid power supplied facilities or subjects. Detector's output fusion and cooperated fuzzy logic control enable to evaluate anticipated threats and dynamically generate the appropriate decisions about real threat existence. It leads to improvement of system protection. As shown in proposed system example, such solution increases correct decisions probability, and eliminates false alarms. Moreover, lower initial cost, hardware failures amount, and energy consumption is achieved when a detector supports two or more subsystems. Additionally, more complete picture is obtained about the facility or subject state, especially in unattended mode.

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Project: Mitigation of stochastic effects in high-bitrate all-optical networks.

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