A fuzzy cognitive maps–petri nets energy management system for autonomous polygeneration microgrids

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A R T I C L E   I N F O
Article history:
Received 14 July 2011
Received in revised form 3 November 2011
Accepted 31 January 2012
Available online 27 February 2012

Keywords:
Polygeneration
Microgrids
Fuzzy cognitive maps
Petri nets
Particle swarm optimization

A B S T R A C T
Autonomous polygeneration microgrids (APM) are a relatively new approach in covering specific needs like power, potable water and fuel for transportation, in remote areas. This approach has been proved to be technically feasible nowadays and even present itself as an economically viable investment. The initial management system built for this approach is a simple ON/OFF supervisor which can make the APM operate, but not in an optimal way. The devices cannot be operated in part load and as a consequence there is little room for optimization. A combined fuzzy cognitive maps (FCMs)–petri nets (PN) approach has been developed for the energy management of such a system. The PN is used as an activator in the fuzzy cognitive map structure so as to enable different FCMs to be activated depending on the state of the microgrid. This combination forms an integrated approach to the energy management of the microgrid. Using this approach considerable optimization in the design and operation of the microgrid is possible. A methodology for simultaneous and interactive optimization of the energy management system along with the sizing of the various devices of the actual microgrid is implemented. A software platform consisting of TRNSYS, TRNOPT and GenOPT software packages was used for simulation and optimization. Particle swarm optimization is applied both for the sizing of the system and the optimization of the FCM weights and PN parameters. Two microgrids were designed, one based on the FCM–PN energy management system (FPEMS) and one on the ON/OFF approach. The results show that FPEMS manages the energy flows more effectively throughout the year which leads to a considerable decrease in the sizing of the various components of the microgrid.

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1. Introduction

Many parts of the world still do not have access to any major electrical grids. Most of these areas are part of the developing world and also present high levels of poverty [1]. Apart from power, these areas usually have limited access to potable water and fuel for transportation. An integrated approach in order to cover the needs in power, potable water and hydrogen as fuel for transportation was developed in the form of a polygeneration microgrid. This topology was validated through simulations and proved to be an economically viable investment presenting minimal risk [2].

This microgrid’s main components include photovoltaics, a wind turbine, a battery bank, an electrolyzer, a metal hydride storage tank, a fuel cell and a desalination unit. In the initial approach a simple ON/OFF energy management system was used in order to decide the operation of the desalination system, electrolyzer and fuel cell. It was evident that a more sophisticated approach ought to be investigated in order for the devices to be able to operate in part load, which allows better overall management of the available energy. It is known from the literature that the fuel cell [3], electrolyzer [4] and desalination unit [5] present higher efficiencies when operating in part load. Many approaches have been used in the past for the design and implementation of energy management approaches. Vosen and Keller have proposed a neural networks approach [6]. The main disadvantage of such an approach is the data needed for the training of the neural network. Fuzzy logic has also been proposed as an alternative because of the ease in using linguistic rules [7,8], but has the disadvantage of relatively hard optimization of all the membership functions’ parameters. PID control has proved to be inadequate if it is not coupled with a self-tuning controller for the adjustment of its gains [9] or with a hybrid fuzzy-PID controller [10]. FCMs are able to deal with the management of systems and processes which are based on human reasoning process [11,12] and have been proposed to be used as a supervisor in complex control systems [11,13]. Extensions for
the FCMs have been developed as well. A model based on Gray
Systems Theory called Fuzzy Gray Cognitive Maps has been de-
veloped which can be adapted to a wide range of problems, espe-
cially in multiple meaning-based environments with gray uncertainties
[14,15]. This approach has been tested in medical applications [16].
Rule based FCMs are another extension which provides greater ver-
satility [17]. Timed automata based FCMs have been proposed for
applications where dynamic behavior is needed [18]. Intuitionistic
FCM is another extension that takes in consideration any hesitation
of the experts in the determination of the causal relations between
the concepts of a domain [19]. PN are useful for the study of dis-
crete event systems [20]. One of the most important approaches
concerns the supervisory strategy [20]. PN have been proposed in
renewable energy systems for energy management and specifically
for choosing different operating modes of the system [21].

This paper presents the development of a combined FCM and
PN approach for the energy management in an APM. The PN is used
in order to choose different operational modes of the system and
then an FCM decides on the actual operation point of each of the
components. A design and optimization tool based on TRNSYS 16
[22], GenOpt 2.0 [23] and TRNOPT [24] was used. The microgrid
was modeled in TRNSYS. The design process was based on parti-
cle swarm optimization (PSO) realized in GenOpt. TRNOPT acted
as an interface between TRNSYS and GenOpt. The problem faced
in the optimization of the management system is that the sizing
of the microgrid’s components is based on the energy management
system and at the same time the optimization of the management
system is based on the sizes of the various devices of the system.
This means that the two optimization processes should take place
one interactively with the other, at the same time. A methodology
to address this situation has been developed and applied in this
paper. Consequently PSO has been used in this paper twofold, ini-
tially as a design tool for the sizing of the various components of
the microgrid and then as an optimization tool of the PN’s transitions
parameters and the weights of the FCMs used. Using this software
platform the microgrid is sized and its energy management sys-
tem optimized. The operation results of this microgrid are then
compared to a design derived using the initial ON/OFF approach.
From the results it is clear that the FCM–PN energy management
system (FPEMS) presents significant improvement in the energy
management of the microgrid throughout the year. This leads to
a considerable decrease in the sizing of the various components.
Taking in consideration that even using the ON/OFF approach the
investor risk is minimal [2] it is clear that an investment in such a
topology using FPEMS reduces considerably the capital cost of the
system and consequently minimizes the risk associated with such
an investment.

2. Materials and methods

2.1. Microgrid configuration

The microgrid configuration is presented in Fig. 1. The actual
components of the system are:

- **Photovoltaic (PV) array.** A typical monocrystalline silicon pho-
tovoltaic array installed on a one-axis vertical tracker which is
adjusted continuously is used. One axis tracking systems have
been on the market for many years now and their advantages

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>( W_{\text{PROD}} )</th>
<th>potable water produced by the electrolyzer unit (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>slope of the linear equation of the efficiency</td>
<td>( W_{\text{TANK}} )</td>
</tr>
</tbody>
</table>
include reliability and comparable cost with fixed frame systems [25].

- **Wind turbine.** A direct current (DC) generator wind turbine is used.
- **Desalination unit.** A custom made sea water desalination unit equipped with hydraulic energy recovery is used in the microgrid. One such desalination unit has been manufactured and tested extensively at the Agricultural University in Athens [5].
- **Fuel cell.** A typical proton exchange membrane (PEM) fuel cell is used.
- **Electrolyzer.** A typical PEM electrolyzer able to supply hydrogen at high pressure (≈15 bar) is used.
- **Metal hydride hydrogen storage tank.** A typical metal hydride storage tank is used.
- **Hydrogen vehicle.** Two hybrid fuel cell-battery scooters are considered for use in the system [26]. The hybrid fuel cell – battery scooters are assumed to have an average hydrogen consumption of 2.4 Nm³ of H₂/100 km. Such scooters are comparable to 72 cc gasoline scooters.
- **Battery bank.** A typical solar deep discharge lead acid battery bank is used. The DC bus is set at 48 V.
- **Typical market available inverters that can operate in a microgrid topology are used for the PV array, the wind turbine and the fuel cell.** The “Sunny Island” topology that is used in this microgrid is patented by “SMA Solar Technology AG”. Other companies like “Studer Innotec SA” are also developing comparable topologies and devices that can be used in such a microgrid [2].

### 2.2. Fuzzy cognitive maps

FCMs are graphs which represent cause and effect relationships and are used for computational inference processing [27]. Systems can be symbolically represented through FCMs. Concepts are used to present different aspects of the modeled system such as inputs, outputs, rules or intermediate states.

\[ C_i, \quad i = 1, \ldots, N \]

where \( N \) is the total number of nodes.

The value of each concept is fuzzified in the space \([0,1]\).

\[ A_i \in [0, 1], \quad i = 1, \ldots, N \]

These node-concepts are interconnected with arcs which have different weights in order to express their relations. One FCM is depicted in Fig. 2. In order to give values to the weights human knowledge and experience is used. The weights are:

\[ W_{ij} \in [-1, 1], \quad i = 1, \ldots, N \quad \text{and} \quad j = 1, \ldots, N \]

![Fig. 1. Schematic presentation of the microgrid.](image)

When the weight expresses positive causality the weight is positive, when the weight expresses negative causality it is negative and zero declares no relation between the concepts. The weights can be presented in a matrix as below:

\[
W_{i,j} = \begin{pmatrix}
W_{11} & W_{12} & W_{13} & W_{14} & W_{15} \\
W_{21} & W_{22} & W_{23} & W_{24} & W_{25} \\
W_{31} & W_{32} & W_{33} & W_{34} & W_{35} \\
W_{41} & W_{42} & W_{43} & W_{44} & W_{45} \\
W_{51} & W_{52} & W_{53} & W_{54} & W_{55}
\end{pmatrix}
\]

This matrix can be simplified by substituting the weights of the concepts which present no relation with zeros.

\[
W_{i,j} = \begin{pmatrix}
0 & W_{12} & W_{13} & 0 & 0 \\
W_{21} & 0 & W_{23} & 0 & 0 \\
W_{31} & 0 & 0 & 0 & 0 \\
0 & W_{42} & 0 & 0 & W_{45} \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

![Fig. 2. A fuzzy cognitive map.](image)
According to Kosko [28] the values of the concepts are influenced by the rest concepts according to Eq. (1). The FCM reaches a converged state after a number of iterations.

\[
A_i(k + 1) = f \left( A_i(k) + \sum_{j=1}^{n} W_{ij} A_j(k) \right)
\]

(1)

where \( k \) is the iteration counter.

Function \( f \) is the activation function. Four functions have been proposed: the sigmoid function, the hyperbolic tangent function, the step function and the threshold linear function [29].

- The sigmoid function is presented in Eq. (2) where \( c \in (0, +\infty) \) is a steepness parameter. For a small \( c \) value (e.g., \( c = 1 \)) it approximates a linear function and for large values (\( c = 10 \)) it approximates a discrete function [29].

\[
f(x) = \frac{1}{1 + e^{-c x}}
\]

(2)

- The hyperbolic tangent function is presented in Eq. (3). It maps its output in the range \([-1,1]\) for a \( c \) value close to 5 [29].

\[
f(x) = \frac{e^{cx} - e^{-cx}}{e^{cx} + e^{-cx}}
\]

(3)

- The step function is presented in Eq. (4). In order to decrease the subjectivity of the of the step function a value of \( T \) equal to 0.5 is proposed [29].

\[
f(x) = \begin{cases} 
0 & \text{if } x \leq T \\
1 & \text{if } x > T 
\end{cases}
\]

(4)

- The threshold linear function is a derivative of the step function and is presented in Eq. (5) [29].

\[
f(x) = \begin{cases} 
0 & \text{if } x \leq T \\
(x - T) & \text{if } x > T 
\end{cases}
\]

(5)

According to [29] the sigmoid function presents specific advantages than the other concepts. Also the needed output needs to be mapped in the space \([0,1]\). This is why it was decided to use the sigmoid function.

In order to model a process or a controller with an FCM, expert knowledge is needed.

An FCM is usually constructed by a knowledge engineer who acquires domain knowledge from systems experts and uses that knowledge to define the concepts, causal directions and linguistic variables of the edges of the graph. The domain experts identify of causal relationships among the concepts and estimate of causal link strengths with linguistic variables [16].

Experts decide on the important aspects of the system which become the concepts and the weights are set according to the inter-relations of the concepts [30]. Linguistic variables can be used by the experts in order to express the relations of the concepts in a simplified way. First of all negative, positive or no causality is set. After that the influence is described with variables like very weak, weak, strong and very strong [27].

The most important disadvantage of FCMs is the possibility to converge in an undesired steady state. This is why different FCM learning algorithms have been proposed. The first algorithms to be proposed were the differential Hebbian learning, the active Hebbian learning and the nonlinear Hebbian rule. The major disadvantage of the afore mentioned algorithms is the strong dependence of the final weights on the initial weights given by the experts. Other approaches include hybrid nonlinear Hebbian learning – differential evolution algorithm, simulated annealing with genetic algorithms and particle swarm optimization algorithm [31].

Since the APM is a novel concept very few experts exist and also there are no historical operational data. Because of this, it is decided that the initial weight matrix is provided by the authors of this paper and PSO is used for its optimization since its results are not heavily dependent on the initial weight matrix [27].

2.3. Petri nets

A petri net (PN) is a weighted bipartite graph which is defined by four parameters \( P, T, A^p \) and \( w \) [20]:

- \( P \): This is the finite set of places and is depicted as one type of node in the graph.
- \( T \): This is the finite set of transitions and is depicted as a second type of node in the graph.
- \( A^p: A^p \subseteq (P \times T) \cup (T \times P) \) and is the set called flow relation which includes the arcs from transitions to places and from places to transitions in the graph.
- \( w \): \( A^p \to \{1, 2, 3, \ldots \} \) is the weight function of the arcs.

It is assumed that \((P, T, A, w)\) have no isolated places or transitions. The set of places is represented by \( P = \{p_1, p_2, \ldots, p_n\}\) and the set of transitions by \( T = \{t_1, t_2, \ldots, t_m\}\), \( |P| = n \) and \( |T| = m \). The weights of the arcs are positive integers and the arcs are represented in the form \((p_i, t_j)\) or \((t_j, p_i)\) [20].

The set of input places to a transition \( t_j \) is represented by \( I(t_j) \) and the output places are presented by \( O(t_j) \) [20].

\[
I(t_j) = \{p_i \in P : (p_i, t_j) \in A\} \quad \text{and} \quad O(t_j) = \{p_i \in P : (t_j, p_i) \in A\}
\]

The mechanism used to indicate in a PN if a condition is met or not is the assignment of tokens to places. If a condition is satisfied, then a token is placed. A marking is defined as the way the tokens are assigned to a PN [20]. A marking \( M \) is an \( m \)-vector, \((M(p_1), \ldots, M(p_n))\), where the number of tokens in the place \( p_i \) is denoted by \( M(p_i) \). The initial marking of the PN is \( M_0 \), where \( M_0 \to \{0, 1, 2, \ldots\} \). All possible markings of the PN that can be reached from \( M_0 \) is the set \( R(M_0) \) [32].

The movement of tokens through the PN presents the state transition function of the PN. This is called firing [20]. A transition is enabled if there are at least \( w(p,t) \) (the weight from \( p \) to \( t \)) tokens in the inputs of place \( t \). If a transition is enabled it might fire or it might not. If it is fired then \( w(p,t) \) tokens are removed from place \( t \) inputs and are added to the outputs according to the weight of the arc from \( t \) to \( p \) (\( w(t,p) \)).

The flow matrix or incidence matrix \( FM = [a_{ij}] \) of a PN with \( n \) transitions and \( m \) places is defined as an \( n \times m \) matrix of integers, where its typical entry is given by [33]:

\[
a_{ij} = w(i,j) - w(j,i)
\]

(6)

The control vector \( u_k \) is defined as an \( n \times 1 \) column vector of \( n - 1 \) zeros and one with its value equal to 1. The vector is given by \( u = [s_1, s_2, \ldots, s_m] \) where \( s_j \in \{0, 1\} \). This position indicates that it has fired at the \( k \)th firing. The state equation is formed as follows [33]:

\[
M_k = M_{k-1} + FM^T u_k
\]

(7)

where \( FM^T \) is the transpose of the flow matrix.

A typical petri net graph is presented in Fig. 3.

3. Optimization method

Optimizations take place in two discrete cases in this paper. The first one is for the sizing of the microgrid’s components and
the second for the optimization of the FCM’s weights and the PN transition parameters. The software used for this is based on a three level structure. The simulation level (TRNSYS), the PSO optimization level (GenOpt) and the interface for their communication (TRNOPT). This structure is presented in Fig. 4.

For the sizing of the microgrid it is decided that the optimal design is the one that fulfills the technical constraints and also presents the lowest Net Present Cost (NPC) for a 20 year investment period. The four technical constraints are:

- No deep discharging of the battery bank is allowed. The fractional State of Charge (SOC) never drops below 20%.
- No water shortage is allowed. This means that the potable tank never gets empty.
- No hydrogen shortage is allowed. This means that the metal hydride tank used for hydrogen storage never gets empty.
- The stored potable water and hydrogen in the end of the year are equal or higher than the stored quantities in the beginning of the year.

The penalties calculation is presented in Fig. 5 and the cost function for the sizing of the microgrid is presented in Eq. (8).

For the optimization of the FCM weights and the PN transition parameters the above technical constrictions still apply. This time the minimum SOC, minimum stored H2 and minimum potable water in the tank are recorded throughout the year. These values are then normalized and added together. Since the software algorithm tries to minimize the cost function, this sum is deducted from the maximum possible sum in order for the best system to have the lowest value of the cost function. This is presented in Eq. (9). The FCM weights and PN transition parameters combination which presents the lowest value in Eq. (10) is the best.

\[
CF1 = NPC + \sum_{t=1}^{8760} \left[ p_b(t) + \sum_{t=1}^{8760} p_{H_2}(t) + \sum_{t=1}^{8760} p_W(t) + p_S \right]
\]

\[
OPTP = \left( 100 - SOC^{\text{MIN}} \right) \times 100 + \left( 1 - \left( \frac{H_2^{\text{MIN}}}{H_2^{\text{TANK}}} \right) \right) \times 10,000 + \left( 1 - \left( \frac{W^{\text{MIN}}}{W^{\text{TANK}}} \right) \right) \times 10,000
\]

\[
CF2 = OPTP + \sum_{t=1}^{8760} p_b(t) + \sum_{t=1}^{8760} p_{H_2}(t) + \sum_{t=1}^{8760} p_W(t) + p_S
\]

where NPC, Net Present Cost for a 20 year period; \( p_b \), battery penalty; \( p_{H_2} \), hydrogen penalty; \( p_W \), water penalty; \( p_S \), tanks penalty. If the stored water and/or stored hydrogen are less in the end of the year than its beginning another 100,000€ are added; \( SOC^{\text{MIN}} \), the minimum fractional SOC throughout the year; \( H_2^{\text{MIN}} \), the minimum quantity of hydrogen in the metal hydride tank throughout the year; \( H_2^{\text{TANK}} \), the volume of the metal hydride tank; \( W^{\text{MIN}} \), The minimum quantity of water in the potable water tank throughout the year; \( W^{\text{TANK}} \), the volume of the potable water tank.

The optimizations take place using the GenOpt software package. The PSO algorithm has been used. The optimization methodology used in this work has been presented in [2]. The parameters for the PSO proposed by Papageorgiou et al. [27] are used for all optimizations.

4. Simulation

4.1. Simulation components

Routines present in TRNSYS are used to simulate the photovoltaic array, wind turbine and battery and user written ones for the hydrogen subsystem, the desalination unit and the controllers.

4.1.1. PEM fuel cell

A typical PEM fuel cell is modeled according to experimental test results from literature [3]. A linear efficiency curve for the fuel cell is considered.

\[
P_{FC} = P_{FC}^\text{nominal} \cdot P_{FC}^\text{AC}
\]

\[
EFF_{FC} = (A_{FC} \cdot OP_{FC}) + B_{FC}
\]

\[
H_{CONS} = \frac{P_{FC}}{EFF_{FC} \cdot LHV_{H_2}} \cdot TS
\]

where \( P_{FC} \), power produced by the fuel cell; \( OP_{FC} \), fractional operation point of the fuel cell given by FPEMS; \( P_{FC}^\text{nominal} \), nominal power of the fuel cell; \( EFF_{FC} \), efficiency of the fuel cell for the given time step; \( A_{FC} \), slope of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the fuel cell; \( B_{FC} \), the Y axis intercept of the linear equation of the efficiency. This is determined by linear curve fitting to the performance curve supplied by the manufacturer of the fuel cell; \( H_{CONS} \), hydrogen consumed by the fuel cell; \( LHV_{H_2} \), lower heating value of hydrogen; \( TS \), a parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.
4.1.2. PEM electrolyzer unit

A typical PEM electrolyzer is modeled according to experimental test results concerning the efficiency at specific power levels from literature [4]. A linear efficiency curve for the fuel cell is considered.

\[ P_{EL} = \eta_{EL} \cdot P_{EL, nom} \]  
\[ \eta_{EL} = \frac{\text{the EL efficiency}}{\text{the EL efficiency}} \]  
\[ P_{PROD} = \frac{P_{EL}}{1 - \eta_{EL}} \cdot TS \]  

where \( P_{EL} \) is the power consumed by the electrolyzer unit; \( \eta_{EL} \) is the fractional operation point of the electrolyzer unit given by FPEMS; \( P_{EL, nom} \) is the nominal power of the electrolyzer unit; \( \eta_{EL} \) is the efficiency of the electrolyzer unit for the given time step; \( A_{EL} \) is the slope of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit; \( B_{EL} \) is the Y axis intercept of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit; \( P_{PROD} \) is the hydrogen produced by the electrolyzer unit; \( LHVH_2 \) is the lower heating value of hydrogen; TS, a parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.

4.1.3. Desalination unit

A typical RO desalination unit equipped with energy recovery is modeled [5,34]. A linear efficiency curve for the desalination unit is considered.

\[ P_{DS} = \eta_{DS} \cdot P_{DS, nom} \]  
\[ \eta_{DS} = \frac{\text{the DS efficiency}}{\text{the DS efficiency}} \]  
\[ W_{PROD} = \frac{P_{DS}}{SEC_{DS}} \cdot TS \]  

where \( P_{DS} \) is the power consumed by the desalination unit; \( \eta_{DS} \) is the fractional operation point of the desalination unit given by FPEMS; \( P_{DS, nom} \) is the nominal power of the electrolyzer unit; \( SEC_{DS} \) is the specific energy consumption for the given time step; \( A_{DS} \) is the slope of the linear equation of the specific energy consumption. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit; \( B_{DS} \) is the Y axis intercept of the linear equation of the specific energy consumption. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit; \( W_{PROD} \) is the potable water produced by the electrolyzer unit; TS, a parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.

4.2. Simulation parameters

The microgrid is responsible for covering the needs of a settlement on a small island in the Aegean Sea, Greece. Typical meteorological data of the Cyclades island complex is used in the simulations. The settlement comprises four households equipped with energy saving devices, with 16 residents. The peak power demand is considered to be 3.2 kW and the average daily energy consumption to be 20 kWh. The 16 residents consume 3.84 m³ of potable water at a daily basis for all their needs (drinking, bathing, laundry and cooking). Two hybrid scooters are used to cover the mobility needs of all the residents. These 2 scooters cover 50 km each daily on average and the corresponding daily fuel consumption is considered to be 2.4 Nm³ H₂. The scooters are refilled daily in the afternoon. The simulation time step is equal to 1 h.

5. Energy management approaches

5.1. The ON/OFF approach

5.1.1. General description

The ON/OFF energy management approach is based on three schemes that run in parallel [34].

a. Double hysteresis control scheme

This scheme is used so that the devices are not turned on and off continuously in boundary conditions. Four parameters are used and are presented in Fig. 6. Two SOC points, high and low, for the operation of the fuel cell (\( FC_{high} \) and \( FC_{low} \)), and two SOC points, high and low again, for the consumptions (\( CON_{high} \) and \( CON_{low} \)).

\[ FC_{high} = \text{at 45%}, FC_{low} = \text{at 25%}, CON_{high} = \text{at 85%}, \text{and CON}_{low} = \text{at 65%} \]

b. Load forecast

The power balance of the microgrid is used for the operation of the fuel cell and the option to turn on the desalination unit and electrolyzer at the same time. If there is a fuel cell ON command from the first scheme and the power balance is positive then the fuel cell is not turned on because it is expected that the SOC will rise. If there is a consumption ON command and the energy balance is positive then both the electrolyzer and desalination units are turned on. Otherwise the third scheme decides which consumption to activate.

c. Hierarchy of the consumptions

Water is considered to be the most important product of the microgrid. This way the management scheme is programmed to aim in having a reserve in the potable water tank adequate to cover the needs for 3 days. If only one of the consumptions is to be turned on after the second scheme then the water in the potable water tank is checked. If it can cover the needs for more than three days then the electrolyzer is turned on, otherwise the desalination unit is turned on.

The ON/OFF management approach is realized in TRNSYS.

5.1.2. Components’ sizing of the ON/OFF microgrid

Because of the simplicity of the ON/OFF controller the sizing of the microgrid based on this approach is a one step process. PSO is used for the optimization of the sizes of the various components [2] (Table 1).

The search space for the optimal microgrid featuring the ON/OFF management approach is presented in Table 2. A typical 7.5 kW DC wind turbine is considered for this system. Also the PV panels are considered to be connected in two rows in parallel. The possible microgrid combinations amount to 914,760. The optimization process of the PSO algorithm is negligible in duration in comparison.

![Fig. 6. Double hysteresis control scheme.](image-url)
with the time that is needed for the simulations to take place. One yearly simulation needs about 1–2 s and for the PSO configuration that was used 1938 simulations took place.

5.2. FPEMS

5.2.1. General description

FPEMS is an energy management system based on a FCM–PN approach. PN is introduced in order to propose a supervisory strategy of an energy management system for APM. FPEMS is presented in Fig. 7.

The PN is used to decide the operational modes of the microgrid, whereas three FCMs are used to determine the operational state of the fuel cell, electrolyzer and desalination unit. FPEMS uses the frequency of the microgrid, SOC and the available water in the potable water tank as inputs.

As in the ON/OFF approach water is again considered to be the most important product of the system. That is why FPEMS aims to have enough water in the potable water tank for 3 days. This is a safety measure if there is some failure in the system. In three days the microgrid can be fixed or arrangements for transportation of water can take place.

Table 1
PSO settings.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Ibest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighborhood size</td>
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<tr>
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</tr>
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<tr>
<td>Social acceleration constant</td>
<td>2.05</td>
</tr>
<tr>
<td>Constriction gain</td>
<td>0.729</td>
</tr>
</tbody>
</table>

The selection of the operating mode is based on a PN. The different conditions for the movement from one state to another are expressed as:

\[
t_1: \text{SOC < SOCL, where SOCL (SOC low) is a set point of SOC from which and below the fuel cell should be turned on.}
\]

\[
t_2: \text{SOC > SOCM, where SOCM (SOC medium) is a set point of SOC from which and above one or both the consumptions (electrolyzer, desalination unit) should be turned on.}
\]

\[
t_3: W_{\text{TANK}} > W_{\text{3D}}, \text{where } W_{\text{3D}} \text{ is the potable water needed to cover the needs for 3 days.}
\]

\[
t_4: W_{\text{TANK}} < W_{\text{3D}}.
\]

\[
t_5: \text{SOC > SOCL.}
\]

\[
t_6: \text{SOC < SOCM or } (W_{\text{TANK}} < W_{\text{3D}}).
\]

\[
t_7: \text{SOC < SOCM or } (W_{\text{TANK}} > W_{\text{3D}}).
\]

There are four modes that can be set which are presented in Table 3.

The flow matrix or incidence matrix FM, of this PN is as follows:

\[
FM = \begin{bmatrix}
-1 & 1 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 1 & -1 \\
1 & -1 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & -1 & 0
\end{bmatrix}
\]

With the above flow matrix and Eq. (7) the PN can be modeled. As it is seen in Fig. 7 the FCMs of Mode 3 and Mode 4 are the same apart from Concept 3 taking the place of Concept 4 and vice versa, without changing anything else in the FCM. Because of this Mode 3 can give priority to the electrolyzer and Mode 4 to the desalination unit in the same manner. This approach simplifies the

Table 2
Optimization variables for ON/OFF management strategy.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lowest value</th>
<th>Highest value</th>
<th>Step</th>
<th>Optimal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical monocrystalline modules rated at 150 Wp each in series</td>
<td>22</td>
<td>30</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Rated power of the fuel cell (W)</td>
<td>300</td>
<td>500</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Rated power of the electrolyzer unit (W)</td>
<td>800</td>
<td>1200</td>
<td>100</td>
<td>1200</td>
</tr>
<tr>
<td>Metal hydride tank storage capacity (Nm³ of H₂)</td>
<td>15</td>
<td>20</td>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td>Potable water tank volume (m³)</td>
<td>40</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Rated power of the desalination unit (W)</td>
<td>1500</td>
<td>2200</td>
<td>100</td>
<td>1700</td>
</tr>
<tr>
<td>Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)</td>
<td>600, 800, 1000, 1200, 1500, 1750, 2000</td>
<td>1200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 7. FPEMS diagram.](image-url)
system by having only 4 weights to optimize instead of 8, where at the same time the needed operational demands from the energy management system are met. FPEMS is realized in TRNSYS.

5.2.2. Methodology for microgrid sizing and energy management design

FPEMS presents a higher complexity than the ON/OFF approach since the weights of the FCM and the PN’s transitions parameters have to be optimized simultaneously and interactively with the sizing of the components of the actual microgrid. The methodology approach realized in this paper comprises the following steps:

1. Knowledge engineer and domain experts decide on the fuzzification and defuzzification methods and the initial weights of the FCM and the transition parameters of the PN are set.
2. The microgrid is sized using PSO based on the results of step 1.
3. The FCM weights and PN transition parameters are optimized based on the sizing derived in step 2 using PSO again.
4. Finally, a new sizing of the microgrid’s components takes place with the use of the optimized parameters for the FCM weights and PN transition parameters that are provided by the optimization results of step 3.

5.2.3. First step for the microgrid sizing and FPEMS design

There are very few experts of this topology because of its novelty. The opinions of the four authors of this paper are used. First the experts’ opinions on the 2 parameters of the PN’s transitions were put forward (SOCL and SOCM) and are presented in Table 4, along with the linguistic variables used. As far as the weights of the FCMs are concerned first it was agreed unanimously by all the experts if the relations between the concepts were positive or negative. The experts’ opinions are presented in Table 4, along with the linguistic variables used. Using the centroid defuzzification method (COG) the linguistic values are transformed in numerical values [35]. These are also presented in Table 4. In Figs. 9–12 the membership functions for the fuzzification procedure are presented. The initial values of the FCM weights and the PN parameters are presented in the last column of Table 4.

The fuzzification method of the inputs of the FCM is agreed as follows:

- Frequency ($F$)

The modeled microgrid is based on the SMA Sunny Island topology. In this topology the frequency of the microgrid is used for the control of all the connected inverters. If the central inverter sees that the battery bank is getting fully charged it starts to increase the frequency of the microgrid from 50 Hz up to 52 Hz so as to protect the battery from overcharging. When the inverters connected to the energy producers (pv, wind, etc.) detect a

<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petri net modes.</td>
</tr>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPEMS parameters and weights.</td>
</tr>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>SOCL</td>
</tr>
<tr>
<td>SOC</td>
</tr>
<tr>
<td>W$_{15}$</td>
</tr>
<tr>
<td>W$_{25}$</td>
</tr>
<tr>
<td>W$_{13}$</td>
</tr>
<tr>
<td>W$_{14}$</td>
</tr>
<tr>
<td>W$_{23}$</td>
</tr>
<tr>
<td>W$_{24}$</td>
</tr>
</tbody>
</table>

EL, extremely low; VL, very low; L, low; RL, relatively low; M, medium; EB, extremely big; VB, very big; B, big; RB, relatively big.
higher frequency they start to decrease the power they give to the microgrid and they cut the supply completely when the frequency reaches 52 Hz. When there is an energy deficit in the microgrid the frequency is decreased gradually down to 49 Hz [36]. The frequency fuzzification is presented in Fig. 8, where FF is the fuzzified frequency.

SOC

Due to the different microgrid operational characteristics especially in Mode 2 in comparison with Modes 3 and 4 two different approaches are agreed to be used.

- **Mode 2**
  
  \[ \text{FSOC} = \frac{\text{SOC} - \text{SOCL}}{\text{SOC}} \]  
  (20)

  where FSOC is the fuzzified SOC.

- **Modes 3 and 4**
  
  \[ \text{FSOC} = \frac{\text{SOC} - \text{SOCM}}{100 - \text{SOCM}} \]  
  (21)

Since the output of the FPEMS corresponds to the operational state of the devices, this number should be in the range [0,100]. Given Eqs. (1) and (2), the maximum and minimum theoretical output values of the FCM in boundary operation are calculated. Based on that the following normalization equations are formed:

\[ \text{OP}_{\text{FC}} = 100 \cdot \frac{C_5 - 0.66}{0.29} \]  
(22)

\[ \text{OP}_{\text{EL}} = 100 \cdot \frac{C_3 - 0.34}{0.53} \]  
(23)

\[ \text{OP}_{\text{DS}} = 100 \cdot \frac{C_4 - 0.34}{0.53} \]  
(24)

Explanation is given below on how the numbers 0.66, 0.29, 0.34 and 0.53 are calculated. Two boundary states are considered for all devices. Eq. (22) is concerned with the operation of the fuel cell which corresponds to \( C_5 \). When the SOC reaches zero and the frequency of the microgrid reaches 49 Hz, the fuel cell should be turned on fully. For these conditions FF = \( C_1 = 1 \) and FSOC = \( C_2 = 1 \). It is assumed that the weights take their extreme values (\( W_{12} = 1 \) and \( W_{25} = 1 \)). This is decided because the PSO search space in step 3 will be \( [W_{ij}] \in [0,1] \). \( C_5 \) is then calculated using Eqs. (1) and (2) following 15 iterations and is equal to 0.95. The opposite boundary condition occurs when the frequency of the microgrid reaches 52 Hz and the SOC reaches the highest value for the PN to choose this mode then FF = \( C_1 = 0 \) and FSOC = \( C_2 = 0 \) the fuel cell should be turned off. \( C_5 \) is then calculated using Eqs. (1) and (2) following 15 iterations and is equal to 0.66. This means that \( C_5 \) can theoretically take values in the space \( [0.66,0.95] \) for \( [W_{ij}] \in [0,1] \). The range is \( 0.95 - 0.66 = 0.29 \).

Eq. (23) is concerned with the electrolyzer. The electrolyzer should be turned fully on when the frequency of the microgrid reaches 52 Hz and the battery is fully charged (SOC = 100). For these conditions FF = \( C_1 = 0 \) and FSOC = \( C_2 = 1 \). We assume that the weights take their extreme values (\( W_{1j} = 1 \) (\( W_{23} = 1 \) and \( W_{13} = -1 \)). This was decided because the PSO search space in step 3 will be \( [W_{ij}] \in [0,1] \). \( C_3 \) is then calculated using Eqs. (1) and (2) following 15 iterations and is equal to 0.87. When the frequency of the microgrid reaches 49 Hz and the battery reaches its lowest point for the PN to choose this mode then FF = \( C_1 = 1 \) and FSOC = \( C_2 = 0 \) the electrolyzer should be turned off. Again assuming that \( W_{ij} = 1 \), \( C_3 \) is calculated using Eqs. (1) and (2) following 15 iterations and is equal to 0.34. So \( C_3 \) can take theoretically values in the space \( [0.34,0.87] \) for \( [W_{ij}] \in [0,1] \). The range is \( 0.87 - 0.34 = 0.53 \). The same applies for Eq. (24) which corresponds to the desalination unit.

Due to technical constriction of the devices if any of the operational states is calculated to be less than 30, the devices remain turned off.

5.2.4. Second step for the microgrid sizing and FPEMS design

After the first step is completed a sizing of the system takes place using PSO. The weights of the FCMs and the parameters of the PN are presented in the last column of Table 4. The search space along with the optimal values is presented in Table 5. The minimum and maximum values are decided after completing a small number of simulations manually. Again, as in the ON/OFF approach microgrid, a typical 7.5 kW DC wind turbine is considered and the PV panels are considered to be connected in two rows in parallel.

5.2.5. Third step for the microgrid sizing and FPEMS design

The third step includes the optimization using PSO for the parameters of the PN and the weights of the FCMs. The search space is presented in Table 6. These values further minimize the cost function presented in Eq. (10). The optimized weights are presented in the last column of Table 6.

The values of the weights along the optimization procedure are presented in Fig. 13.

### Table 5

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lowest value</th>
<th>Highest value</th>
<th>Step</th>
<th>Optimal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical monocristalline modules rated at 150 Wp each in series</td>
<td>10</td>
<td>17</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Rated power of the fuel cell (W)</td>
<td>300</td>
<td>500</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Rated power of the electrolyzer unit (W)</td>
<td>500</td>
<td>1000</td>
<td>100</td>
<td>800</td>
</tr>
<tr>
<td>Metal hydride tank storage capacity (Nm³ of H2)</td>
<td>15</td>
<td>20</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Potable water tank volume (m³)</td>
<td>40</td>
<td>45</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>Rated power of the desalination unit (W)</td>
<td>1500</td>
<td>2000</td>
<td>100</td>
<td>1600</td>
</tr>
<tr>
<td>Capacity rating of each of the 2 V batteries, 24 are used for a 48 V DC bus (Wh)</td>
<td>600, 800, 1000, 1200, 1500</td>
<td>800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lowest value</th>
<th>Highest value</th>
<th>Step</th>
<th>Optimal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCL</td>
<td>22</td>
<td>35</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>SOCM</td>
<td>45</td>
<td>65</td>
<td>1</td>
<td>52</td>
</tr>
<tr>
<td>W15</td>
<td>0</td>
<td>1</td>
<td>0.01</td>
<td>0.96</td>
</tr>
<tr>
<td>W25</td>
<td>0</td>
<td>1</td>
<td>0.01</td>
<td>0.47</td>
</tr>
<tr>
<td>W13</td>
<td>–1</td>
<td>0</td>
<td>0.01</td>
<td>–0.82</td>
</tr>
<tr>
<td>W14</td>
<td>–1</td>
<td>0</td>
<td>0.01</td>
<td>–0.99</td>
</tr>
<tr>
<td>W23</td>
<td>0</td>
<td>1</td>
<td>0.01</td>
<td>0.94</td>
</tr>
<tr>
<td>W24</td>
<td>0</td>
<td>1</td>
<td>0.01</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**Fig. 12.** Membership functions for positive fuzzy FCM weights.
5.2.6. Fourth step for the microgrid sizing and FPEMS design

The fourth and final step of the combined FPEMS design and components’ sizing procedure is the sizing of the microgrid based on the optimal parameters for the PN and the optimal weights of the FCMs that were derived in the third step. The search space and the results are presented in Table 7. As it is seen the optimization of the weights gave a further decrease in the Cost Function CF1 (Eq. (8)). The expensive metal hydride tank was decreased considerably, along with the desalination unit with a slight increase of the installed PV power.

6. Results – comparison of FPEMS and the ON/OFF approach

Comparing the installed sizes of the two optimized microgrids as presented in Tables 2 and 7 it is clear that by using FPEMS the sizes of most system components decrease. Notably the installed PV power, electrolyzer and battery bank are decreased by almost 34%.

Comparative energy bar charts are presented in Fig. 14. It is evident that FPEMS microgrid produces less energy yearly, but can manage it more effectively in order to cover the same needs. In both cases the fuel cell operates as a backup energy source. In the case of the ON/OFF approach it is turned on for 42 h throughout the year, while for the FPEMS it is needed only for 5 h.

In Fig. 15 the yearly fluctuation of hydrogen in the metal hydride tank is presented. As it is seen, seasonal storage of hydrogen clearly takes place. FPEMS with a smaller tank can cover the same needs.

In Fig. 16 the yearly fluctuation of water in the potable water tank is presented. As it is seen the optimization process favors large storage tanks that are not emptied extremely in accordance with the design principle to always have at least 3 days of water in the potable water tank. The needs in water for three days amount to about 11.5 m$^3$ of water. The part load operation of the desalination unit of the FPEMS microgrid gives more flexibility. The device can be operated in lower operational states when there is a slight excess of energy in order to produce water. In the ON/OFF approach when the power production is low for some consecutive days the desalination unit cannot be turned on at all, because it needs to be run in the nominal power, and, hence, there is a rapid drop in the

Table 7
Optimization variables for step 4.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lowest value</th>
<th>Highest value</th>
<th>Step</th>
<th>Optimal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical monocrystalline modules rated at 150 Wp</td>
<td>14</td>
<td>20</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Rated power of the fuel cell (W)</td>
<td>300</td>
<td>500</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Rated power of the electrolyzer unit (W)</td>
<td>500</td>
<td>900</td>
<td>100</td>
<td>800</td>
</tr>
<tr>
<td>Metal hydride tank storage capacity (Nm$^3$ of H$_2$)</td>
<td>16</td>
<td>20</td>
<td>0.5</td>
<td>16</td>
</tr>
<tr>
<td>Potable water tank volume (m$^3$)</td>
<td>40</td>
<td>45</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>Rated power of the desalination unit (W)</td>
<td>1400</td>
<td>1700</td>
<td>100</td>
<td>1500</td>
</tr>
<tr>
<td>Capacity rating of each of the 2V batteries, 24 are used for a 48 V DC bus (Wh)</td>
<td>600, 800, 1000, 1200</td>
<td>800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
available stored water. Three typical days were chosen to present the different behavior of the two energy management systems.

The first typical day is the 20th of April. The power diagrams are presented in Fig. 17. In both approaches the SOC of the battery is low from the previous day. For the ON/OFF approach the fuel cell was turned on from the previous day because the SOC dropped below 25% and keeps it on until almost 9 o’clock when the Sun has risen and the PV has produced enough power to charge the battery. FPEMS on the other hand is more flexible and turns on the fuel cell in part load for only 5 h managing in one hand not to let the SOC drop.

![Fig. 17. Power figures for the 20th of April.](image1)

![Fig. 18. Power figures for 1st of August.](image2)
below 20% and at the other hand making economy on hydrogen fuel. For the ON/OFF approach the bigger PV array charges fully the batteries by afternoon and since there is available power in the system both the electrolyzer and the desalination unit are turned on. When the Sun sets and the produced power is not enough to operate both devices, the desalination unit is turned off and the electrolyzer remains on until midnight when the SOC drops below 65% and consequently it is turned off. For the FPEMS microgrid as soon as the batteries get relatively charged in the afternoon the desalination unit and electrolyzer are turned on in part load. As the Sun sets and the wind turbine produced power drops both devices are turned off.

In Fig. 18 the power figures for the 1st of August are presented. The solar and wind potential remain high for this day. For both microgrids the battery remains almost fully charged throughout the day. For the ON/OFF approach the electrolyzer and desalination unit remain on continuously. For FPEMS the devices remain on constantly again but in two occasions they operate in a lower operational point. This happens initially early in the morning before sunrise when the wind turbine produced power drops and the energy balance in the microgrid becomes negative. The second time this is noticed is in the evening, when the Sun has set and the wind turbine produced power again drops.

The third typical day is October 1st and it is presented in Fig. 19. For the ON/OFF approach SOC fluctuates a lot throughout the day from just below 50% to almost fully charged. The wind potential is low for this day, but the PV produce considerable power. At about noon when the PV power has charged the battery both the electrolyzer and desalination units are turned on. When the Sun starts to set the available power in the system drops and so the desalination unit is turned off. The electrolyzer remains on until the evening when it is turned off because of the low SOC. FPEMS on the other hand presents much better energy management. Even though its battery is of lower capacity SOC remains between 60% and 80% throughout the day. The electrolyzer is operated in part load continuously apart from some time late in the evening. The desalination unit is turned on in part load for some time early in the morning because of the relatively high SOC and turned off again. During the day, because of the PV produced power it is turned on again and is turned off when the Sun starts to set.

7. Conclusions

From the results it is clearly seen that a sophisticated energy management system is mandatory for achieving optimal operation of the APM. The initially used ON/OFF strategy can make the APM topology operational, but the management of the energy flows throughout the year is far from optimal. With the use of FPEMS the sizes of all components are reduced considerably – in many cases at the range of 34%.

Part load operation of the devices is very important. Operating in part load presents higher efficiencies and also only the needed goods’ quantities are produced. Summarizing:

- FPEMS is managing the overall energy in the microgrid more effectively.
- By allowing the devices to operate in part load higher efficiencies are accomplished.
- The sizing of the microgrid can be decreased considerably. Consequently the cost of the system is also decreased significantly making the investment more attractive.

It has to be mentioned that the use of PSO for the optimization of the FCM weights and the PN’s transitions parameters can result to a better energy management system. There was an overall improvement in comparison with the weights and parameters given by the experts. The proposed methodology for designing and optimizing a management system based on FCM and PN, along the actual sizing of the microgrid can give excellent results even if there are no historical data for such a system or the experience is minimal.
Future work includes the realization and field testing of the FPEMS in the experimental microgrid installed at the Agricultural University of Athens.

References