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Performance investigation of a hybrid renewable power generation and storage system using systemic power management models

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ABSTRACT

Hybrid renewable power generation systems considering storage of energy and/or hydrogen involve considerable complexity as heterogeneous equipment need to be interconnected and activated or deactivated at different time instances. This work employs generic and flexible decision making models to develop complex power/hydrogen management strategies and investigate their performance on systems integrating multiple power generation and storage devices. These models significantly facilitate the analysis of both a standalone power generation and storage system forming a microgrid currently in operation as well as three interconnected microgrids of different functionalities considered in this work. These systems are used to investigate the performance of a large number of power management strategies developed using the proposed models.

1. Introduction

Hybrid renewable power generation systems are attracting a lot of interest due to technological advances enabling efficient utilisation of renewable sources while satisfying the requirement for reduced CO_2 emissions [1,2]. To address the intermittent nature of largely unpredictable environmental phenomena, such systems transform RES (renewable energy sources) into dependable power flows by simultaneous utilisation of different types of conversion equipment and storage media (e.g. PVs (photovoltaic) panels, WGs (wind generators), chemical accumulators etc.). Hydrogen-based technologies are also receiving considerable attention as they enable flexible and long-term energy storage, increasing the capacity provided by conventional accumulators. The combination of renewable energy and storage equipment producing, consuming or satisfying different loads locally is generally defined as a microgrid [3], while several microgrids connected together form a grid [4]. Standalone applications include mainly cases of microgrids or small size grids serving consumers of reduced or no access to the conventional power grid [5].

Regardless of their classification, hybrid renewable power generation systems result in infrastructures combining multiple subsystems of heterogeneous characteristics that need to operate smoothly and efficiently within an integrated, overall system. Their coordinated operation involves significant complexities due to the existence of a very large number of interactions affecting the overall system performance. The intense variability of renewable energy sources inflicts a varying temporal behaviour resulting in significant operating transitions among temporally different connections between sub-systems. In such a context, decisions regarding the appropriate time instance to activate/deactivate different subsystems, the duration of operation of a particular subsystem under specific technical constraints, and the amount or type of energy carrier to use (e.g. power or hydrogen) are generally addressed within three hierarchically structured levels [6]. At a higher level decisions involve the exchange of power among different microgrids forming a grid, while at the immediately lower level decisions are necessary locally at each microgrid to determine efficient

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Nomenclature

$C_{l,j}$	capacity of accumulator l in state j.
$E_{M\rightarrow N}(t)$	binary variable that describes the state of connection between nodes M and N.
$F_m^{\text{In}}(t)$	input vector of node m.
$F_m^{\text{In},j}(t)$	input at state j of node m.
$F_m^{\text{Out}}(t)$	output vector of node m.
$F_{m\rightarrow n}^{\text{Out},j}(t)$	output of node m that goes to node n at state j.
$F_m^{\text{Out},j}(t)$	output at state j of node m.
G^{Acc}	set of all accumulators.
G^{Conv}	Set of all converters.
H_2HP	hydrogen in high pressure.
H_2LP	hydrogen in low pressure.
H_2O	water.
L	logical operator.
$P_{M\rightarrow N}^{\text{SOAcc}_N^l}(t)$	binary variable that describes the connection between nodes M and N based on the state l of an accumulator N.
POW	electrical power.
S	set of all subsystems in a system of microgrids.
$\text{SF}_n^j(t)$	side feed at state j of node n.
SOAcc^l	state of accumulator l.
St	set of states.
$a_{m\rightarrow n}^j(t)$	proportion of output m that goes to node n at state j.
$c_{p,m\rightarrow n}$	condition p for the connection m to n.
$f_m^j(\cdot)$	function that describes the conversion of node m at state j.
h	time variable.
$\text{stp}_{m\rightarrow n}^{\text{SOAcc}^l}(t)$	stopping value of hysteresis zone of accumulator l for the connection m to n.
$\text{str}_{m\rightarrow n}^{\text{SOAcc}^l}(t)$	starting value of hysteresis zone of accumulator l for the connection m to n.
t	time.
t^-	previous time instant.
$\varepsilon_{m\rightarrow n}^{\text{Avl}}(t)$	binary variable that describes the availability of energy/material of node m to feed node n.
$\varepsilon_{m\rightarrow n}^{\text{Req}}(t)$	binary variable that describes the requirement of energy/material of node n from node n.
$\varepsilon_{m\rightarrow n}^{\text{Gen}}(t)$	binary variable that describes a general condition for the connection of node m to node n.
$\varepsilon_{m\rightarrow n}(t)$	binary variable that describes the state of connection between nodes m and n.
$\rho_{m\rightarrow n}^{\text{SOAcc}^l}(t)$	binary variable that describes the connection between nodes m and n that is based on the state of accumulator l.

Subscripts/superscripts

Acc	accumulator.
Conv	converter.
In	index indicating a flow stream entering a node.
M,N	different nodes at the level of interconnected microgrids.
Out	index indicating a flow stream leaving a node.
m, n, k	different nodes at the level of interconnected devices within a microgrid.
j	state of a flow.
p	condition id number.

modes of interoperation among the incorporated subsystems. At these two levels, system behaviours and responses can be studied in time-scales of lower resolution to plan efficient overall control schemes, often coined in published works as PMS (power management strategies). On the other hand, the final level involves the implementation of power management on individual devices hence decisions are mainly required at finer time-scales ranging from simple ON–OFF control to PID controllers or even more advanced control methods [7].

The presented work addresses the two higher decision-making levels considering only the main sub-systems or devices utilised to transform, produce or store power in hybrid power generation systems with the aim to investigate the development of overall PMSs. Devices such as DC/AC buses or converters/inverters which are mainly relevant at the lower level are therefore not considered. This work is originally motivated by the need to develop and implement efficient PMSs for systems in the form of three standalone renewable power generation and storage microgrids which will subsequently be interconnected. The individual microgrid systems have been constructed by the authors and are currently in operation, while their interconnection is also in implementation. In the latter case, technical issues regarding equipment of power electronics associated with the lower control level are currently investigated and overcome to be able to implement the higher level power management strategies. The more complex of the three systems combines energy/hydrogen storage with RES, while the remaining two are simpler versions of different functionality (e.g. without hydrogen infrastructure or utilising different power sources). The existing systems currently operate smoothly using simple PMSs developed and implemented based on the two higher decision making levels. However, additional such strategies need to be investigated to improve their operation, as well as to facilitate their interconnection.

To date, several research publications investigate similar systems at the levels considered in this work to address the increasingly difficult decision-making as more subsystems are considered [8–20]. Quite often the models employed to address the varying temporal behaviour of such systems are case-specific. Furthermore, once the PMSs have been pre-determined a set of rules is derived to resolve when a device will be activated in standalone applications or when a microgrid will request or supply energy from/to another microgrid [21]. These rules are expressed by a series of *if-else* statements in the form of a logical flow chart [14–17,21–25]. Clearly, these approaches are limiting in view of the need to investigate a large number of potential temporal interactions among different sub-systems prior to selecting the ones with the highest performance. Representations of power management decisions in the form of *if-else* statements are marginally feasible for even smaller systems and impractical for the interconnection of microgrids as they lack the flexibility necessary to generate and compare multiple potential alternatives.

In a different line of work, an increasing number of publications are being reported aiming to facilitate efficient integration of the heterogeneous devices often considered in power/heating/cooling cogeneration systems [26], or to propose control laws for the devices within each microgrid or between microgrids [27]. The former works address the structural design of flowsheets by proposing conceptual models developed around generic flow characteristics. In particular, work in Refs. [28–30] proposes the 'energy hub' concept supporting the development of networks based on generic processing tasks. This has subsequently been upgraded [31,32] into the 'power node' concept where different tasks are represented simultaneously, while all potential options of energy usage and losses are implicitly considered. The presented applications involve mainly incoming natural gas, power and heat streams employed in heat and power co-generation infrastructures. By a similar token, work presented in Ref. [33] has proposed a matrix-based modelling approach enabling a generic representation of flows in tri-generation systems. Recently, a mathematical programming formulation has been proposed for the operational planning of residential energy supply chain networks based on microgeneration technologies [34]. Superstructure-based approaches have also been proposed for the optimum design of distributed energy supply systems and applied in the development of combined heating and cooling networks (CHP) [26,35,36]. The design of residential CHP microgrids has also been addressed using a model-predictive control formulation within a systemic model [37] Combined cooling, heating and power generation microgrids have also been addressed through a generic superstructure-based approach in the form of a mixed-integer linear programming model, applied in the design of residential polygeneration systems [38]. Furthermore, various energy control methods have been proposed to improve the system's performance by controlling the state of each device in the microgrid or the exchange of energy among the microgrids. These methods may take into account the technical properties of the microgrid/grid, economic factors, weather forecast and others. For example in Refs. [5,9,10,39] weather and load predictions were taken into account and used in deterministic and stochastic optimisation methods in order to control the energy flow within the system. On the other hand in Ref. [11] a fuzzy logic controller was used in order to achieve the optimum balance between the energy supplied to the load from the fuel cell and the battery. Work in Ref. [40] addresses the issue of optimum reconfiguration of an electrical distribution system, considering different ways to meet the demanded loads by scheduling appropriate branch switching-based predicted demand and generation. Finally, in Refs. [21–23,41] few energy management methods have been proposed and compared including the usage of hysteresis zones to prolong the anticipated lifetime of different systems.

This work builds on the above research efforts to develop and investigate the performance of different and complex PMSs for the standalone systems previously described as well as for their interconnection into an overall power exchange system. Firstly a generic network model is described for the representation of the hybrid power generation systems investigated in this work. Subsequently, this model serves as a platform for a generic approach aiming to facilitate the derivation of various PMSs in a simple and flexible way. The proposed approach is utilised for the representation of the activation/deactivation switching of devices at different time-instances within a flowsheet in a flexible and inclusive manner, regardless of the complexity and size of the investigated flowsheet. It can be used as a simulation tool, for the operation under control of the hybrid energy system, in a real system to determine the operation of each device, in a digital signal processor or in a simulation environment without the need for heavy computational power. Its key features are that it remains simple regardless of the system complexity or the need to alter PMSs during the operation, while it easily serves the need to know exactly which device has been activated and for what reason.

2. System description and significance of power management strategies

2.1. Standalone system

This work is originally motivated by a set of three hybrid standalone power generation systems constructed and currently operating in Greece. The two of them combine batteries for power storage with PVs, or PVs and WGs, while the third also includes a hydrogen production, storage and usage infrastructure. Features of the three systems are presented in Table 1. This section describes major features of the third system, while the remaining two may be considered sub-classes of this one. Fig. 1 illustrates a schematic diagram of the considered standalone system. The system consists of a LD (local load), PVs (photovoltaic panels), WGs (wind generators), a BAT (battery), a DSL (diesel generator), a FC (fuel cell), an EL (electrolyser), a BF (buffer tank), a CP (compressor), a FT (final tank) and a WT (water tank).

The proper operation of such systems is based on the development and utilisation of a particular PMS [42], with key issues involving a) the appropriate time instance to activate/deactivate each device and b) and the time length in which it needs to remain active. The time instance and duration of activation are important operating parameters as they determine the frequency of activation for each device. While less frequent activations reduce the wear and tear of sensitive equipment such as ELs and FCs, requests for hydrogen production or utilisation might be frequent to best serve the goal of satisfying the demanded load. These two conflicting behaviours must be balanced within an appropriate PMS. The frequency of activations is often regulated through the use of hysteresis zones [41]. Instead of deactivating a device exactly after it is no longer needed, it remains active because the prolonged operation avoids very frequent switching. In a similar manner a device remains idle if it was idle in the previous time instance. The temporal length of this hysteresis is an important decision parameter in a PMS, clearly associated with the capacity of the available accumulators. If a device is to remain active producing power or hydrogen, the corresponding accumulators need to be able to store the generated excess. In the opposite case they need to be able to serve the demanded operations with the available reserves. Clearly, all these features provide an indication of the numerous potential operating options that unravel, as different subsystems are required to interoperate based on the availability of excessive power in the system or the lack of it. A PMS supports the identification of efficient operating decision alternatives, while maintaining a smooth system operation and protecting the individual components from irregular operating patterns that would eventually compromise their efficiency. The use of logical flow charts to represent PMSs results in complications. In fact, the use of logical flow charts in previous published work [22,43] has been a prohibitive factor to develop and study additional cases on top of the obvious choices.

2.2. Interoperation of multiple microgrids

Several standalone energy systems (microgrids) can be connected together to form an overall system (or as otherwise called, a grid) and exchange electrical energy (it is also possible to have exchange of hydrogen or even water) when this is required. There are many technical issues on how these systems can be connected

Table 1
Microgrid parameters.

	System 1	System 2	System 3
Load	1 kW	1 kW	1 kW
PV (66.64 W rated power)	200	100	217
WG (1 kW rated power)	N/A	3	3
DSL	1010 W	1010 W	1010 W
BAT	4000 Ah	2000 Ah	3000 Ah
FC	N/A	N/A	1000 W
EL	N/A	N/A	5000 W
BF	N/A	N/A	8 bar, 1 m^3
FT	N/A	N/A	20 bar, 443 m^3

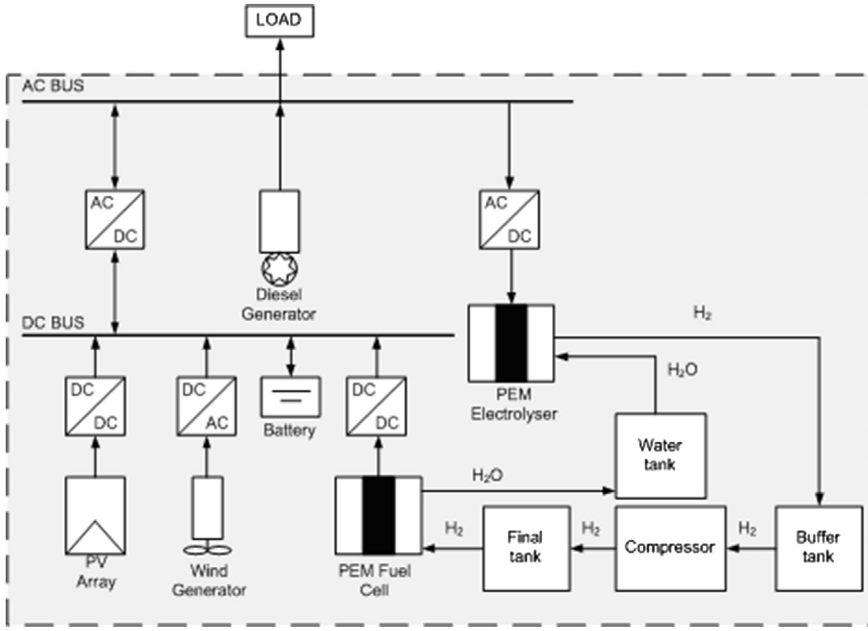

Fig. 1. Standalone microgrid used as a case study.

together (for example AC or DC connection, voltage levels, frequency and power quality issues, communication between the microgrids [44–48], type of energy exchange [49] or even safety) [4]. The focus in this work will be on the conditions that must be satisfied in order for a system to stop supplying energy to a (the) load and demand energy from adjacent systems. Three existing systems are considered incorporating different infrastructure (Table 1). This causes power deficiencies or excesses among the systems which may be addressed through power exchange. It is assumed that:

- Each system N has its own local load (LD^N) and there is an external connection between the systems, i.e. the loads are not connected on a main bus (Fig. 2).
- Each one of the three systems is assigned with its own PMS ($PMS_N^{Lo}, N = \{1,2,3\}$).
- A higher level overall PMS (or controller), namely PMS^{Hi} oversees the strategies below and decides the sources and sinks for power exchange.

These assumptions imply that when an individual system N requests and receives power, this is emulated as if it is assigned with an additional energy source internally regulated based on PMS_N^{Lo}. It is possible for a system to request a constant or variable energy flow and the remaining systems to supply equal or not amount of energy.

A PMS^{Hi} has to be proposed for the overall system which considers all the potential states of the incorporated accumulators/storage tanks $SOAcc_N^l(t)$ (where $l \in \{BAT,FT,BF,WT\}$, $N \in \{system_1, system_2 \ldots\}$), instead of only $SOAcc_N^{BAT}(t)$ mainly considered in published works. In such a case the complexity increases significantly which makes imperative the need for an efficient method that can describe and adapt any possible PMS. Now up to 4 accumulators (see Table 1) in each sub-system might need to be checked by PMS^{Hi} and in the case of three systems similar to the one described in the previous section, the PMS^{Hi} will have to handle 3 times as many parameters as the PMS^{Lo} and numerous combinations of them that result in different performances. Furthermore, it is possible to consider additional conditions imposed on the power exchange, for example a system may not release energy during the winter months to other connected systems or when a DSL is active within the overall system. Clearly, for simple systems it is straightforward to use simple *if-else* statements, but for complicated cases it becomes impractical.

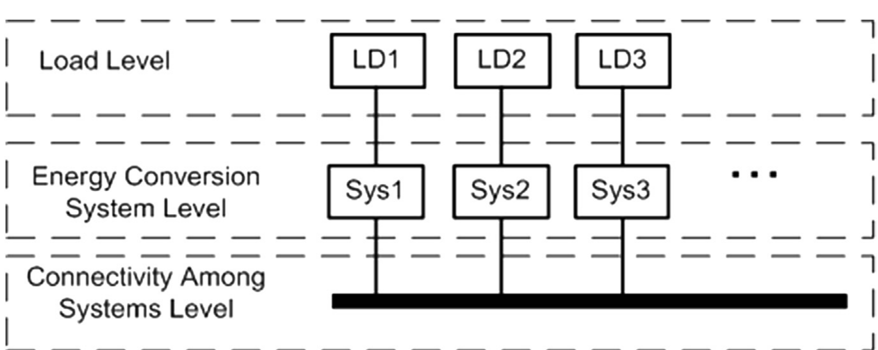

Fig. 2. Grid topology.

3. Network-based system representation

Prior to developing a systemic representation for power management decisions it is necessary to use a generic model capturing all the flows among interconnected devices or systems, regardless of the tasks that they perform. In the most general case a system may be treated as a network considering devices as nodes and material streams or energy lines as edges. In systems like the one presented in Fig. 1, the devices can have multiple input and output flows or signals which can be in various forms or otherwise called states. For example the output of the FC is electrical power and water. Therefore the first step in modelling such systems is to define all the states. In the system shown in Fig. 1 the states are: St = {POW, H_2HP, H_2LP, H_2O}. An immediate consequence of this is that in a network flow model each output and input are vectors with each element to correspond to a state $j \in$ St.

For the isolated microgrids, two general classes of devices may be considered; those storing a state, and those transforming a state to another state. Devices belonging to the first class will be called Acc (accumulators) while devices of the second class will be called Conv (converters). Hence, in the systems investigated in this work a set G^{Acc} of accumulators can be defined, consisting of the BAT that stores POW, the FT that stores H_2HP, the BF that stores H_2LP and the WT that stores H_2O. A similar set G^{Conv} of converters consists of the PVs, the WGs and the DSL that transform external inputs to electrical power, the EL that combines water and electrical energy to produce hydrogen in low pressure, the FC that produces electrical energy and water from hydrogen, and the CP that steps up the pressure of hydrogen. The load can also be considered as a converter, but without any output flow. Hence the aforementioned sets are G^{Acc} = {BAT,FT,BF,WT} and G^{Conv} = {PV,WG,DSL,EL,FC,CMP,LD}.

Based on the above observations the equation describing the flows of energy or materials among different devices is of the following form:

$$F_n^{\mathrm{In},j}(t) = \mathrm{SF}_n^j(t) + \sum_l \left(\varepsilon_{l\to n}(t)\cdot F_{l\to n}^{\mathrm{Out},j}(t)\right) + \sum_k \left(\varepsilon_{k\to n}(t)\cdot F_{k\to n}^{\mathrm{Out},j}(t)\right) \quad (1)$$

where $l \in G^{\mathrm{Acc}}$, $k \in G^{\mathrm{Conv}}$, $n \in G^{\mathrm{Conv}} \cup G^{\mathrm{Acc}}$, $F_{l\to n}^{\mathrm{Out},j}(t)$ is the output of accumulator l that goes to device n, in state j, $\mathrm{SF}_n^j(t)$ is a possible external signal or flow (e.g. solar radiation) and $\varepsilon_{l\to n}(t)$ is a binary variable that becomes 1 when accumulator l feeds device n in state j. The same holds for accumulators. More precisely, if there is no physical connection between l (or k) and n the corresponding variable ε is 0. If two devices are physically connected (e.g. the FC and the BAT) then the variable ε is 1 when the connection is active (e.g. the FC is supplying energy to the BAT) and 0 when the connection is not active. To activate a connection (and hence set the corresponding variable ε to 1) a set of conditions must be satisfied as it will be described in the next section. Note that it is also possible to have a converter establishing at a specific instant an active connection with respect to one state but not with respect to another. This is because in principle variables ε depends on state j. In the systems considered in this work it is assumed that a converter is active or not for all states, hence superscript j is omitted from ε for brevity. However, it is necessary to maintain j in terms $F_n^{\mathrm{In},j}$ and $F_{k\to n}^{\mathrm{Out},j}$, due to the different streams entering and leaving each device. Further, note that a flow leaving a converter k (or accumulator l) at state j may be distributed to different devices based on the following equation:

$$F_{k\to n}^{\mathrm{Out},j}(t) = a_{k\to n}^j(t)\cdot F_k^{\mathrm{Out},j}(t) \quad (2)$$

where $a_{k\to n}^j(t)$ is the proportion of the output of the converter k that goes to device n at state j, with $\sum_n (a_{k\to n}^j(t)) = 1$ and the same equations holding for accumulators. The latter are characterised by the amount of stored energy or material which can generally be defined as the normalised amount of the stored state:

$$\mathrm{SOAcc}^l(t) = \mathrm{SOAcc}^l\left(t^-\right) + \frac{F_{k\to l}^{\mathrm{In},j}(t) - F_{l\to k}^{\mathrm{Out},j}(t)}{C_l} \quad (3)$$

where $\mathrm{SOAcc}^l(t)$ is the amount of stored state j in accumulator l at time instant t, the symbol t^- is used to account for the previous observation instant and C_l is the capacity of accumulator l in state j. In other words, symbol j should normally be included in the previous terms. However, in order to avoid unnecessary complexion and considering that in our systems an accumulator can store only one state (the BAT can only store electrical power, the FT can only store hydrogen in high pressure and so on) the symbol of the state is removed from the variables SOAcc and C.

At the higher level of the overall system, each sub-system (i.e. a microgrid) integrating different groups of devices can be considered as a node of a network; then a similar analysis can be applied. Considering a set S of connected microgrids comprising the overall system, the expression for the input to each microgrid is:

$$F_N^{\mathrm{In},j}(t) = \sum_M \left(E_{M\to N}(t)\cdot F_{M\to N}^{\mathrm{Out},j}(t)\right) \quad \forall M,N \in S \quad (4)$$

Notice that in (4) the variable $E_{M\to N}$ indicates when microgrid M will supply energy to microgrid N, in a similar manner to variable $\varepsilon_{m\to n}$ (where m may generally stand for an accumulator l or converter k) used to indicate the connection between devices m and n. In other words, while (4) describes flows between different microgrids, (1)–(3) describe flows within each microgrid.

4. Power management representation

4.1. General PMS structure

To address the complexity issues raised in Section 2 it is necessary to define the variables ε (similarly E for systems of microgrids) for each connection in a systemic and flexible way. Decisions whether to activate a connection between devices m and n are generally based on three conditions considering:

- The availability of material or energy from device $m \in G$, described by $\varepsilon_{m\to n}^{\mathrm{Avl}}(t)$.
- The requirement for material or energy of device $n,m \in G, \forall n \neq m$, described by $\varepsilon_{m\to n}^{\mathrm{Req}}(t)$.
- Additional specific conditions that are not associated with the above two and may be desirable, described by $\varepsilon_{m\to n}^{\mathrm{Gen}}(t)$.

4.1.1. Elaboration of variable ε

The variable $\varepsilon_{m\to n}(t)$ (a similar analysis can be followed for a connection in a system of microgrids) can be defined in the form of a logical proposition as follows:

$$\varepsilon_{m\to n}(t) = L\left(\varepsilon_{m\to n}^{\mathrm{Avl}}(t), \varepsilon_{m\to n}^{\mathrm{Req}}(t), \varepsilon_{m\to n}^{\mathrm{Gen}}(t)\right) \quad (5)$$

where L is a logical connective operator determined by the structure of the PMS. The variables $\varepsilon^{\mathrm{Avl}}_{m\to n}(t), \varepsilon^{\mathrm{Req}}_{m\to n}(t)$ are used to express the conditions imposed in the desired PMS as follows:

$$\begin{aligned}\varepsilon^{\mathrm{Avl}}_{m\to n}(t) &= L^{\mathrm{Avl}}_{m\to n}\left(\rho^{\mathrm{SOAcc}^{l_1}}_{m\to n}(t)\right)\forall l_1\in G^{\mathrm{Acc}}\\ \varepsilon^{\mathrm{Req}}_{m\to n}(t) &= L^{\mathrm{Req}}_{m\to n}\left(\rho^{\mathrm{SOAcc}^{l_2}}_{m\to n}(t)\right)\forall l_2\neq l_1\in G^{\mathrm{Acc}}\end{aligned} \quad (6)$$

where $\rho^{\mathrm{SOAcc}^l}_{m\to n}(t)$ is a binary variable that becomes 1 when a condition of the form $c_{p,m\to n}, p\in\mathbb{N}$ is satisfied after applying logical operators $L^{\mathrm{Avl}}_{m\to n}$ and $L^{\mathrm{Req}}_{m\to n}$. Such conditions depend on the material or energy stored in the accumulators (i.e. SOAcc values). Although variables ρ are defined separately for each $\varepsilon^{\mathrm{Avl}}_{m\to n}(t), \varepsilon^{\mathrm{Req}}_{m\to n}(t)$ it is not possible in the investigated systems to consider the same SOAcc as a function of both $\varepsilon^{\mathrm{Avl}}_{m\to n}(t)$ and $\varepsilon^{\mathrm{Req}}_{m\to n}(t)$. When an accumulator requests energy or materials, this automatically means that there is a deficiency in this accumulator and vice versa hence l_1 and l_2 are mutually exclusive. As a result, l will be hereafter used instead of l_1 and l_2 for brevity in both parts of (5), maintaining that when accumulator l is considered in $\varepsilon^{\mathrm{Avl}}_{k\to n}(t)$, then only accumulators $l-|G^{\mathrm{Acc}}|$ will be considered in $\varepsilon^{\mathrm{Req}}_{k\to n}(t)$ and vice versa.

4.1.2. Elaboration of variable ρ in the context of variable ε

From definition, the variable ρ accounts for ON–OFF switching of the devices, since this can be described by activation of a connection between two devices based on a simple condition imposed on SOAcc. However, prior to presenting a generic expression that quantifies this behaviour, it also necessary to somehow take into account the possibility of having a hysteresis zone. The decision whether to activate a connection between two devices in the presence of a hysteresis zone is the result of the following logical tests that depend on the accumulated energy or material (for the specific hysteresis zone shown in Fig. 3):

- If SOAcc^l is higher than a pre-specified limit $stp^{\mathrm{SOAcc}^l}_{m\to n}(t)$ the connection is inactive.
- If SOAcc^l is less than $\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)$ the connection is active.
- If SOAcc^l is in the interval between parameters $\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)$ and $\mathrm{stp}^{\mathrm{SOAcc}^l}_{m\to n}(t)$, the connection will be:
  - Inactive if it was inactive in the previous instance
  - Active if it was previously activated.

Using the above parameters, variable ρ can generally be defined as a function of the associated conditions imposed on SOAcc^l as follows:

$$\rho^{\mathrm{SOAcc}^l}_{m\to n}(t) = \left[\mathrm{SOAcc}^l(t) < \mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)\right]\vee \left[\left[\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t) < \mathrm{SOAcc}^l(t) < \mathrm{stp}^{\mathrm{SOAcc}^l}_{m\to n}(t)\right]\wedge\left[\varepsilon_{m\to n}\left(t^-\right) = 1\right]\right] \quad (7)$$

Note that in (7) the first inequality represents the simple ON–OFF behaviour, while the subsequent expression represents the hysteresis behaviour. Also note that there is only a need to investigate three accumulation areas associated with each accumulator l, namely below $\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)$, between $\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)$ and $\mathrm{stp}^{\mathrm{SOAcc}^l}_{m\to n}(t)$, and above $\mathrm{stp}^{\mathrm{SOAcc}^l}_{m\to n}(t)$, to determine whether a connection will be activated. This is simply repeated for every connection. This can be useful in complex systems as it is a lot easier to check many simple rules rather than one but complicated [16]. Apparently, the values of the limits $\mathrm{str}^{\mathrm{SOAcc}^l}_{m\to n}(t)$ and $\mathrm{stp}^{\mathrm{SOAcc}^l}_{m\to n}(t)$ may become decision variables for the investigation of the overall system performance.

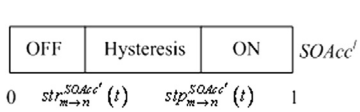

Fig. 3. General hysteresis zone.

In order to allow for the flexibility to ignore a specific condition or proposition, the binary variables $r^{\mathrm{SOAcc}^l}_{m\to n}(t)$ are defined and combined with the variables $\rho^{\mathrm{SOAcc}^l}_{m\to n}(t)$ using a logical operator $L^{\mathrm{SOAcc}^l}_{m\to n}$ as follows:

$$\varepsilon^q_{m\to n}(t) = L^q_{m\to n}\left(L^{\mathrm{SOAcc}^l}_{m\to n}\left(\rho^{\mathrm{SOAcc}^l}_{m\to n}(t), r^{\mathrm{SOAcc}^l}_{m\to n}(t)\right)\right), \quad l\in G^{\mathrm{Acc}},\ \ q\in\{\mathrm{Avl},\mathrm{Req}\} \quad (8)$$

Finally, the variable $\varepsilon^{\mathrm{Gen}}_{k\to n}(t)$ is determined by the specific requirements imposed in a PMS (for example extra temporal conditions) and is analysed in the next sections.

4.2. Standalone microgrid containing multiple devices

In this section a specific PMS for the standalone system is developed with the main goal to ensure that the local load is always adequately supplied. This PMS will then be transformed into different PMSs in Section 5 by adding, removing or altering conditions. The considered PMS consists of the conditions stated in Table 2 in the form of loose, user-prescribed sentences to illustrate how they can be easily transformed into logical propositions using the described method.

In order to protect the devices, in the conditions $c_{1,\mathrm{DSL}\to\mathrm{BAT}}$, $c_{1,\mathrm{FC}\to\mathrm{BAT}}$, $c_{1,\mathrm{EL}\to\mathrm{BF}}$, $c_{2,\mathrm{CP}\to\mathrm{FT}}$ a hysteresis zone is also considered. These propositions can easily be described by the aforementioned approach. For example, in the system considered in this work the FC involves three conditions that must be satisfied. The first one determines if the battery (i.e. the receiving node) requests energy. This will happen when (condition $c_{1,\mathrm{FC}\to\mathrm{BAT}}$) the $\mathrm{SOAcc}^{\mathrm{BAT}}(t)$ is either below $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ or between $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ and $\mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ and the FC is already active (hysteresis zone in $c_{1,\mathrm{FC}\to\mathrm{BAT}}$). In this case, the logical proposition is:

$$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t) = \left[\mathrm{SOAcc}^{\mathrm{BAT}}(t) < \mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right]\vee \left[\left[\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t) < \mathrm{SOAcc}^{\mathrm{BAT}}(t) < \mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right]\wedge\left[\varepsilon_{\mathrm{FC}\to\mathrm{BAT}}\left(t^-\right) = 1\right]\right] \quad (9)$$

As only one condition is set for $\varepsilon^{\mathrm{Req}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ it holds that $\varepsilon^{\mathrm{Req}}_{\mathrm{FC}\to\mathrm{BAT}}(t) = \rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$. The next two conditions ($c_{2,\mathrm{FC}\to\mathrm{BAT}}$ and $c_{3,\mathrm{FC}\to\mathrm{BAT}}$) determine the availability from the FC to supply power to

Table 2
Operating conditions for each device.

Connection	Condition
$c_{1,PV\to BAT}$	"The battery is not completely charged"
$c_{1,WG\to BAT}$	"The battery is not completely charged"
$c_{1,DSL\to BAT}$	"The battery is almost discharged"
$c_{1,FC\to BAT}$	"The state of charge of the battery is low"
$c_{2,FC\to BAT}$	"There is available hydrogen in the FT"
$c_{3,FC\to BAT}$	"The WT is not completely full"
$c_{1,EL\to BF}$	"The battery is charged"
$c_{2,EL\to BF}$	"The BF is not completely full"
$c_{3,EL\to BF}$	"There is available water in the WT"
$c_{1,CP\to FT}$	"The FT is not completely full"
$c_{2,CP\to FT}$	"There is available hydrogen in the BF"

the battery, i.e. the $\text{SOAcc}^{\text{FT}}(t)$ is above a specific value $\text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FT}}}(t)$, without a hysteresis zone and the $\text{SOAcc}^{\text{WT}}(t)$ is below a specific value $\text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FC}}}(t)$ without a hysteresis zone. In this case $\text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FT}}}(t) = \text{stp}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FT}}}(t)$ and $\text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}} = \text{stp}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}}$ and the logical propositions are:

$$\rho_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FT}}}(t) = \text{SOAcc}^{\text{FT}}(t) > \text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{FT}}} \quad (10)$$

$$\rho_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}}(t) = \text{SOAcc}^{\text{WT}}(t) < \text{str}_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}}(t) \quad (11)$$

Hence the node FC can deliver power to the battery when:

$$\varepsilon_{\text{FC}\rightarrow\text{BAT}}^{\text{Req}}(t) = \rho_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) \vee r_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) \quad (12)$$

$$\varepsilon_{\text{FC}\rightarrow\text{BAT}}^{\text{Avl}}(t) = \bigcap_{l}\left[r_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{l}}(t) \vee \rho_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{l}}(t)\right], \quad l \in \{\text{FT}, \text{WT}\} \quad (13)$$

Notice that equations (12) and (13) also include variables r which are further elaborated below. The decision to activate the connection FC→BAT therefore results from equation (13) where extra conditions can easily be added through $\varepsilon_{\text{FC}\rightarrow\text{BAT}}^{\text{Gen}}(t)$. For example, assume that in order to activate the FC, the DSL must not be active. This is expressed as follows:

$$\varepsilon_{\text{FC}\rightarrow\text{BAT}}^{\text{Gen}}(t) = \neg\left[\varepsilon_{\text{DSL}\rightarrow\text{BAT}}\left(t^{-}\right)\right] \quad (14)$$

Hence the final proposition can be simply calculated through equation (5). Note that in (12)–(14) specific logical operators were used that correspond to a particular PMS. Of course it is possible to use different operators that will result in different PMSs. To demonstrate the utilisation of the r variables, assume that at one specific instant t the DSL is OFF, the FT has adequate H2HP but the WT is almost full and hence the FC will remain OFF. To overcome this (for example in a case of emergency), in equations 12–14 the variable $r_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}}(t)$ is set to 1 while keeping the rest of the r variables at 0, the variable $\rho_{\text{FC}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{WT}}}(t)$ is set to 0 while keeping the rest of the ρ at 1 and the $\varepsilon_{\text{DSL}\rightarrow\text{BAT}}(t^{-})$ variable is set to 0. The entire set of propositions for the previously described PMS is presented in Tables 3 and 4.

4.3. Overall system of interconnected microgrids

For a system of microgrids a similar approach will be followed as above. The PMS^{Hi} will determine if a microgrid requires energy and also if it has available energy for the requesting microgrid. As a case study here it is assumed that in the considered PMS^{Hi} microgrid M will send energy to microgrid N based on the following conditions:

- $c_{p,\text{M}\rightarrow\text{N}}$ = The SOAcc^{l} of N is low ($l \in$ {BAT,FT} for p = {1,2})
- $c_{p,\text{M}\rightarrow\text{N}}$ = The SOAcc^{l} of M is high ($l \in$ {BAT,FT} for p = {3,4})

Again this is easily described in the form of logical variables as follows:

$$c_{p,M\rightarrow N} : P_{M\rightarrow N}^{\text{SOAcc}_N^{l}}(t) = \text{SOAcc}_N^{l} < \text{str}_{M\rightarrow N}^{\text{SOAcc}_N^{l}}, \quad l \in \{\text{BAT}, \text{FT}\} \text{ for } p = \{1, 2\} \quad (15)$$

$$c_{p,M\rightarrow N} : P_{M\rightarrow N}^{\text{SOAcc}_M^{l}}(t) = \text{SOAcc}_M^{l} > \text{str}_{M\rightarrow N}^{\text{SOAcc}_M^{l}}, \quad l \in \{\text{BAT}, \text{FT}\} \text{ for } p = \{3, 4\} \quad (16)$$

where the variables P, R are similar to the variables ρ, r used in the standalone systems. Note that at the level of PMS^{Hi} no hysteresis is considered in order to avoid unnecessary complexity (even though it can easily be included). Hence only a single parameter is needed to determine the limit for activation or deactivation of energy exchange between two microgrids, namely $\text{str}_{M\rightarrow N}^{\text{SOAcc}_N^{l}}$. Based on (15), (16) a possible logical proposition is:

$$E_{M\rightarrow N}^{\text{Req}}(t) = \left(R_{M\rightarrow N}^{\text{SOAcc}_N^{BAT}}(t) \vee P_{M\rightarrow N}^{\text{SOAcc}_N^{\text{BAT}}}(t)\right) \wedge \left(R_{M\rightarrow N}^{\text{SOAcc}_N^{\text{FT}}}(t) \vee P_{M\rightarrow N}^{\text{SOAcc}_N^{\text{FT}}}(t)\right)$$
$$E_{M\rightarrow N}^{\text{Avl}}(t) = \left(R_{M\rightarrow N}^{\text{SOAcc}_M^{\text{BAT}}}(t) \vee P_{M\rightarrow N}^{\text{SOAcc}_M^{\text{BAT}}}(t)\right) \vee \left(R_{M\rightarrow N}^{\text{SOAcc}_M^{\text{FT}}}(t) \vee P_{M\rightarrow N}^{\text{SOAcc}_M^{\text{FT}}}(t)\right) \quad (17)$$

that implies that the system N will see that it has energy deficit when its BAT AND FT are low, the system M will see that it can send

Table 3
Connections of PV→BAT, WG→BAT, DSL→BAT, CP→FT.

Condition	Variable	Proposition
$c_{1,\text{PV}\rightarrow\text{BAT}}$	$\varepsilon_{\text{PV}\rightarrow\text{BAT}}^{q}(t), \quad q \in \{\text{Avl}, \text{Gen}\}$	1
	$\varepsilon_{\text{PV}\rightarrow\text{BAT}}^{\text{Req}}(t)$	$\rho_{\text{PV}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) \vee r_{\text{PV}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$
	$\rho_{\text{PV}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$	$\text{SOAcc}^{\text{BAT}}(t) < \text{str}_{\text{PV}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$
$c_{1,\text{WG}\rightarrow\text{BAT}}$	$\varepsilon_{\text{WG}\rightarrow\text{BAT}}^{q}(t), \quad q \in \{\text{Avl}, \text{Gen}\}$	1
	$\varepsilon_{\text{WG}\rightarrow\text{BAT}}^{\text{Req}}(t)$	$\rho_{\text{WG}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) \vee r_{\text{WG}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$
	$\rho_{\text{WG}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$	$\text{SOAcc}^{\text{BAT}}(t) < \text{str}_{\text{WG}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$
$c_{1,\text{DSL}\rightarrow\text{BAT}}$	$\varepsilon_{\text{DSL}\rightarrow\text{BAT}}^{q}(t), \quad q \in \{\text{Avl}, \text{Gen}\}$	1
	$\varepsilon_{\text{DSL}\rightarrow\text{BAT}}^{\text{Req}}(t)$	$\rho_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) \vee r_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$
	$\rho_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)$	$\left[\text{SOAcc}^{\text{BAT}}(t) < \text{str}_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)\right] \vee \left[\left[\text{str}_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t) < \text{SOAcc}^{\text{BAT}}(t) < \text{stp}_{\text{DSL}\rightarrow\text{BAT}}^{\text{SOAcc}^{\text{BAT}}}(t)\right] \wedge \left[\varepsilon_{\text{DSL}\rightarrow\text{BAT}}(t^{-})\right]\right]$
$c_{1,\text{CP}\rightarrow\text{FT}}$	$\varepsilon_{\text{CP}\rightarrow\text{FT}}^{\text{Avl}}(t)$	$r_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t) \vee \rho_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t)$
$c_{2,\text{CP}\rightarrow\text{FT}}$	$\varepsilon_{\text{CP}\rightarrow\text{FT}}^{\text{Req}}(t)$	$r_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{FT}}}(t) \vee \rho_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{FT}}}(t)$
	$\varepsilon_{\text{CP}\rightarrow\text{FT}}^{\text{Gen}}(t)$	1
	$\rho_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t)$	$\left[\text{SOAcc}^{\text{BF}}(t) > \text{str}_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t)\right] \vee \left[\left[\text{stp}_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t) < \text{SOAcc}^{\text{BF}}(t) < \text{str}_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{BF}}}(t)\right] \wedge \left[\varepsilon_{\text{CP}\rightarrow\text{FT}}(t^{-})\right]\right]$
	$\rho_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{FT}}}(t)$	$\text{SOAcc}^{\text{FT}}(t) < \text{str}_{\text{CP}\rightarrow\text{FT}}^{\text{SOAcc}^{\text{FT}}}(t)$

Table 4
Connections of FC→BAT, EL→BF.

Condition	Variable	Proposition
$c_{1,\mathrm{FC}\to\mathrm{BAT}}$	$\varepsilon^{\mathrm{Avl}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	$\bigcap_{l}\left[r^{\mathrm{SOAcc}^{l}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\vee\rho^{\mathrm{SOAcc}^{l}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right],\ l\in\{\mathrm{FT},\mathrm{WT}\}$
$c_{2,\mathrm{FC}\to\mathrm{BAT}}$		
$c_{3,\mathrm{FC}\to\mathrm{BAT}}$	$\varepsilon^{\mathrm{Gen}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	1
	$\varepsilon^{\mathrm{Req}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\vee r^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$
	$\rho^{\mathrm{SOAcc}^{\mathrm{FT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	$\mathrm{SOAcc}^{\mathrm{FT}}(t)>\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{FT}}}_{\mathrm{FC}\to\mathrm{BAT}}$
	$\rho^{\mathrm{SOAcc}^{\mathrm{WT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	$\mathrm{SOAcc}^{\mathrm{WT}}(t)<\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{WT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$
	$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$	$\left[\mathrm{SOAcc}^{\mathrm{BAT}}(t)<\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right]\vee\left[\left[\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)<\mathrm{SOAcc}^{\mathrm{BAT}}(t)<\mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right]\wedge\left[\varepsilon_{\mathrm{FC}\to\mathrm{BAT}}(t^{-})\right]\right]$
$c_{1,\mathrm{EL}\to\mathrm{B}}$	$\varepsilon^{\mathrm{Req}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	$r^{\mathrm{SOAcc}^{\mathrm{BF}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\vee\rho^{\mathrm{SOAcc}^{\mathrm{BF}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$
$c_{2,\mathrm{EL}\to\mathrm{B}}$	$\varepsilon^{\mathrm{Avl}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	$\bigcap_{l}\left[r^{\mathrm{SOAcc}^{l}}_{\mathrm{EL}\to\mathrm{BF}}(t)\vee\rho^{\mathrm{SOAcc}^{l}}_{\mathrm{EL}\to\mathrm{BF}}(t)\right],\ l\in\{\mathrm{BAT},\mathrm{WT}\}$
$c_{3,\mathrm{EL}\to\mathrm{BF}}$		
	$\varepsilon^{\mathrm{Gen}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	1
	$\rho^{\mathrm{SOAcc}^{\mathrm{BF}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	$\mathrm{SOAcc}^{\mathrm{BF}}(t)<\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BF}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$
	$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	$\left[\mathrm{SOAcc}^{\mathrm{BAT}}(t)>\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\right]\vee\left[\left[\mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)<\mathrm{SOAcc}^{\mathrm{BAT}}(t)<\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\right]\wedge\left[\varepsilon_{\mathrm{EL}\to\mathrm{BF}}(t^{-})\right]\right]$
	$\rho^{\mathrm{SOAcc}^{\mathrm{WT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$	$\mathrm{SOAcc}^{\mathrm{WT}}(t)>\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{WT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$

energy when its BAT OR FT have energy/material. Obviously again different logical operators lead to different PMSs.

5. Implementation

The presented case studies exploit the described methods to investigate a series of different PMSs in terms of their impact to the system performance. Their performance is investigated with the aim to identify PMSs that simultaneously a) minimise the usage of the DSL and b) minimise the loss of energy produced by the RES, while c) protecting the EL and FC from over-utilisation. The systems were studied for a year of operation, starting at 00:00 on the 1st of January until 23:00 on the 31st of December with a sample time of 1 h, hence in this case study $t\in[0,8760]$.

5.1. Power management strategies

As a case study we chose to alter a) the length of the hysteresis zones based on i) operational and ii) temporal conditions and b) the activation conditions of the devices which depend on i) the time of the year and ii) on the power deficit/surplus. All PMSs result from modifications imposed on the PMS described in Section 4. These combinations result in the following 5 PMSs:

1. PMS_1: The first or basic energy management is as the one previously defined in Tables 3 and 4 but all the r variables are set to $0\ \forall\ t$, and the devices are operated based solely on the SOAcc values, thus the ε variables are:

$$\varepsilon_{k\to\mathrm{BAT}}(t)=\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{k\to\mathrm{BAT}}(t),k\in\{\mathrm{PV},\mathrm{WG},\mathrm{DSL}\}\tag{18}$$

$$\varepsilon_{k\to\mathrm{BF}}(t)=\bigcap_{l}\rho^{\mathrm{SOAcc}^{l}}_{k\to\mathrm{BF}}(t)\tag{19}$$

with $l\in\{\mathrm{FT},\mathrm{WT},\mathrm{BAT}\}$ for $k=EL$ and $l\in\{\mathrm{BF},\mathrm{FT}\}$ for $k=CP$ in equation (19).

2. PMS_2: In this PMS the hysteresis zone of the FC and EL depend on the time of the year, i.e. the variables str and stp are not fixed. For example during the summer months it is imposed that $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)=\mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ while during the winter $\mathrm{stp}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)=\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$. Thus the variables $\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ and $\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)$ in Tables 3 and 4 are written as:

$$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)=\left[\mathrm{SOAcc}^{\mathrm{BAT}}(t)<\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\right],t\in[2881,5832]\tag{20}$$

$$\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)=\left[\mathrm{SOAcc}^{\mathrm{BAT}}(t)>\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\right],\quad t\in[0,2160]\cup[6553,8760]\tag{21}$$

3. PMS_3: In this PMS the length of the hysteresis depends on the time interval in which the connections FC→BAT and EL→BF remain active. The time interval is set to 3 h in this case. This condition is represented by the general variables $\varepsilon^{\mathrm{Gen}}_{\mathrm{FC}\to\mathrm{BAT}},\varepsilon^{\mathrm{Gen}}_{\mathrm{EL}\to\mathrm{BF}}$ which become 0 during the considered interval, i.e. variables $\varepsilon_{\mathrm{FC}\to\mathrm{BAT}}(t)$,$\varepsilon_{\mathrm{EL}\to\mathrm{BF}}(t)$ in Tables 3 and 4 are calculated based on equation (5) with:

$$\varepsilon^{\mathrm{Gen}}_{k\to l}(t)=\neg\bigcap_{h=1}^{3}[\varepsilon_{k\to l}(t-h)],\quad l=\mathrm{BAT}\ \text{for}\ k=\mathrm{FC},\quad l=\mathrm{BF}\ \text{for}\ k=\mathrm{EL}\tag{22}$$

and $\varepsilon^{\mathrm{Req}}_{\mathrm{FC}\to\mathrm{BAT}}(t),\varepsilon^{\mathrm{Avl}}_{\mathrm{FC}\to\mathrm{BAT}}(t),\varepsilon^{\mathrm{Req}}_{\mathrm{EL}\to\mathrm{BF}}(t),\varepsilon^{\mathrm{Avl}}_{\mathrm{EL}\to\mathrm{BF}}(t)$ can be found in Tables 3 and 4

4. PMS_4: Now, the operation of the devices depend on the time of the year, i.e. during the summer the FC is not activated even if the $\mathrm{SOAcc}^{\mathrm{BAT}}$ drops below $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}$, similarly for the EL during the winter months. Thus the variables $\varepsilon_{\mathrm{FC}\to\mathrm{BAT}}(t)$,$\varepsilon_{\mathrm{EL}\to\mathrm{BF}}(t)$ in Tables 3 and 4 are written as:

$$\begin{aligned}
\varepsilon^{\mathrm{Req}}_{\mathrm{FC}\to\mathrm{BAT}}(t)&=\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\wedge r^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)\\
r^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)&=0\quad t\in[2881,5832]\\
\varepsilon^{\mathrm{Avl}}_{\mathrm{EL}\to\mathrm{BF}}(t)&=\rho^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\wedge r^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)\\
r^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{EL}\to\mathrm{BF}}(t)&=0\quad t\in[0,2160]\cup[6553,8760]
\end{aligned}\tag{23}$$

5. PMS_5: The final PMS that was tested uses the information of the excess or deficit of energy. Hence the FC will not be activated if there is excess of energy even if the $\mathrm{SOAcc}^{\mathrm{BAT}}(t)$ drops below $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ and similarly the EL will not be activated when there is a deficit of energy. This can be implemented using a number of ways, for example the value of $\mathrm{str}^{\mathrm{SOAcc}^{\mathrm{BAT}}}_{\mathrm{FC}\to\mathrm{BAT}}(t)$ can be set to zero when there is energy surplus. Another option (adopted here) is to add a general condition as before:

$$\varepsilon^{\mathrm{Gen}}_{\mathrm{FC}\to\mathrm{BAT}}(t)=\left[F^{\mathrm{Out,Pow}}_{\mathrm{PV}\to\mathrm{BAT}}+F^{\mathrm{Out,Pow}}_{\mathrm{WG}\to\mathrm{BAT}}-F^{\mathrm{Out,Pow}}_{\mathrm{BAT}\to\mathrm{BAT}}<0\right]\tag{24}$$

$$\varepsilon^{\text{Gen}}_{\text{EL}\to\text{BF}}(t) = \left[F^{\text{Out,Pow}}_{\text{PV}\to\text{BAT}} + F^{\text{Out,Pow}}_{\text{WG}\to\text{BAT}} - F^{\text{Out,Pow}}_{\text{BAT}\to\text{BAT}} > 0\right] \tag{25}$$

5.1.1. System of microgrids

As a case study here, it is assumed that a system will request a constant predefined amount of power and that the other systems will equally contribute. This value will be the load that needs to be covered in the system (1 kW) plus extra energy in order to charge the battery of the microgrid (1 kW). Twenty different PMSs are tested based on 2 major concepts: a) the logical operators, the FC operation and the power consumed by the EL are fixed or not throughout the year and b) the FC delivers a fixed or variable amount of power to the battery. More specifically we have:

1. $\text{PMS}^{\text{Hi}}_{0-5}$: Are the basic PMSs that are distinguished based on the logical operators used to check the state of various accumulators. All parameters remain fixed throughout the year.
2. $\text{PMS}^{\text{Hi}}_{6-10}$: As $\text{PMS}^{\text{Hi}}_{0-5}$ but now the PMS^{Hi} also makes local changes to PMS^{Lo} by changing the power produced by the FC.
3. $\text{PMS}^{\text{Hi}}_{11-15}$: In these PMSs the main goal is time dependant, i.e. while during winter the focus is how to avoid the usage of the DSLs, during summer the goal is to store as much energy as possible in Hydrogen tanks. Local changes are also imposed as now the FC is not activated during the summer months and the EL consumes all the power send by the other 2 microgrids.
4. $\text{PMS}^{\text{Hi}}_{16-20}$: As $\text{PMS}^{\text{Hi}}_{11-15}$ but now the power produced by the FC depends on the energy send to the other 2 microgrids.

Individually the considered PMSs are elaborated as follows:

1. $\text{PMS}^{\text{Hi}}_{0}$ − No energy exchange is allowed, i.e. the 3 microgrids work as standalone systems, hence $E_{M\to N}(t) = 0$, $\forall M, N \in \{1,2,3\}, M \neq N$
2. $\text{PMS}^{\text{Hi}}_{1}$ − The $\text{SOAcc}^{\text{FT}}_{3}$ of the third microgrid is ignored. Only the batteries of all microgrids will be checked for power deficiency, while power will be dispatched only from those with availability and the FT of the last microgrid will not be used:

$$\begin{aligned}
P^{\text{SOAcc}^{\text{BAT}}_{n}}_{M\to N}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{N}(t) < \text{str}^{\text{SOAcc}^{\text{BAT}}_{N}}_{M\to N}(t)\right]\\
P^{\text{SOAcc}^{\text{BAT}}_{m}}_{M\to N}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{M}(t) > \text{str}^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to N}(t)\right]\\
E_{M\to N}(t) &= \bigcap_{l}\left[R^{\text{SOAcc}^{l}_{M}}_{M\to N}(t) \vee P^{\text{SOAcc}^{l}_{M}}_{M\to N}(t)\right],\\
&\quad l \in \{\text{BAT},\text{FT}\}, \forall M, N \in \{1,2,3\}, M \neq N
\end{aligned} \tag{26}$$

3. $\text{PMS}^{\text{Hi}}_{2}$ − The $\text{SOAcc}^{\text{FT}}_{3}$ of the third microgrid will be accounted for using the operator AND for all microgrids. In this case microgrids 1 and 2 will see that there is available energy from microgrid 3 only if the $\text{SOAcc}^{\text{BAT}}_{3}$ AND $\text{SOAcc}^{\text{FT}}_{3}$ are above $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{3\to N}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{3\to N}$. Similarly the third microgrid will see that it needs energy only if its $\text{SOAcc}^{\text{BAT}}_{3}$ AND $\text{SOAcc}^{\text{FT}}_{3}$ are below $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{M\to 3}$:

$$\begin{aligned}
P^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}(t) &= \bigcap_{l}\left[\text{SOAcc}^{l}_{3}(t) < \text{str}^{\text{SOAcc}^{l}_{3}}_{M\to 3}(t)\right], \; l \in \{\text{BAT},\text{FT}\}\\
P^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to 3}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{M}(t) > \text{str}^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to 3}(t)\right]\\
E_{M\to 3}(t) &= \left[R^{\text{SOAcc}^{\text{BAT}}_{m}}_{M\to 3}(t) \vee P^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to 3}(t)\right]\\
&\wedge \left[R^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}(t) \vee P^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}(t)\right], \; \forall M \in \{1,2\}
\end{aligned} \tag{27}$$

$$\begin{aligned}
P^{\text{SOAcc}^{\text{BAT}}_{N}}_{3\to N}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{N}(t) < \text{str}^{\text{SOAcc}^{\text{BAT}}_{N}}_{3\to N}(t)\right]\\
P^{\text{SOAcc}^{\text{BAT}}_{3}}_{3\to N}(t) &= \bigcap_{l}\left[\text{SOAcc}^{l}_{3}(t) < \text{str}^{\text{SOAcc}^{l}_{3}}_{M\to 3}(t)\right], l \in \{\text{BAT},\text{FT}\}\\
E_{3\to N}(t) &= \bigcap_{i}\left[R^{\text{SOAcc}^{\text{BAT}}_{c}}_{3\to N}(t) \vee P^{\text{SOAcc}^{\text{BAT}}_{c}}_{3\to N}(t)\right], \; \forall i \in \{3,1\}, \forall N \in \{1,2\}
\end{aligned} \tag{28}$$

$$\begin{aligned}
P^{\text{SOAcc}^{\text{BAT}}_{N}}_{M\to N}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{N}(t) < \text{str}^{\text{SOAcc}^{\text{BAT}}_{N}}_{M\to N}(t)\right]\\
P^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to N}(t) &= \left[\text{SOAcc}^{\text{BAT}}_{M}(t) > \text{str}^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to N}(t)\right]\\
E_{M\to N}(t) &= \bigcap_{l}\left[R^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to N}(t) \vee P^{\text{SOAcc}^{\text{BAT}}_{M}}_{M\to N}(t)\right],\\
&\quad l \in \{\text{BAT},\text{FT}\}, \; \forall M, \; N \in \{1,2\}, \; M \neq N
\end{aligned} \tag{29}$$

4. $\text{PMS}^{\text{Hi}}_{3}$ − The $\text{SOAcc}^{\text{FT}}_{3}$ of the third microgrid is accounted for using the operator AND for the 1st and 2nd microgrid and the operator OR for the third microgrid. In this case systems 1 and 2 will see that there is available energy from microgrid 3 only if the $\text{SOAcc}^{\text{BAT}}_{3}$ AND $\text{SOAcc}^{\text{FT}}_{3}$ are above $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{3\to N}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{3\to N}$. The third microgrid will see that it needs energy if either its $\text{SOAcc}^{\text{BAT}}_{3}$ and $\text{SOAcc}^{\text{FT}}_{3}$ are below $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{M\to 3}$. The equations are exactly the same as $\text{PMS}^{\text{Hi}}_{2}$ except:

$$P^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}(t) = \bigcup_{l}\left[\text{SOAcc}^{l}_{3}(t) < \text{str}^{\text{SOAcc}^{l}_{3}}_{M\to 3}(t)\right], \; l \in \{\text{BAT},\text{FT}\} \tag{30}$$

5. $\text{PMS}^{\text{Hi}}_{4}$ − The $\text{SOAcc}^{\text{FT}}_{3}$ of the third microgrid is accounted for using the operator OR for the 1st and 2nd system and the operator AND for the third microgrid. In this case the microgrids 1 and 2 will see that there is energy available from microgrid 3 if either the $\text{SOAcc}^{\text{BAT}}_{3}$ AND $\text{SOAcc}^{\text{FT}}_{3}$ of the third microgrid are above $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{3\to N}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{3\to N}$ respectively. While the third microgrid will see that it needs energy only if $\text{SOAcc}^{\text{BAT}}_{3}$ and $\text{SOAcc}^{\text{FT}}_{3}$ are below $\text{str}^{\text{SOAcc}^{\text{BAT}}_{3}}_{M\to 3}$ and $\text{str}^{\text{SOAcc}^{\text{FT}}_{3}}_{M\to 3}$ respectively. The equations are exactly the same as $\text{PMS}^{\text{Hi}}_{2}$ apart from:

$$P^{SOAcc_3^{BAT}}_{3\to N}(t) = \bigcup_l \left[SOAcc_3^l(t) > str^{SOAcc_3^l}_{3\to N}(t)\right], \quad l\in\{BAT, FT\} \quad (31)$$

6. PMS_5^{Hi} – The $SOAcc_3^{FT}$ of the third microgrid is accounted for using the operator OR for all microgrids. In this case the microgrids 1 and 2 will see that there is energy from microgrid 3 if the $SOAcc_3^{BAT}$ AND $SOAcc_3^{FT}$ of the third microgrid are above $str^{SOAcc_3^{BAT}}_{3\to n}$ & $str^{SOAcc_3^{FT}}_{3\to n}$ respectively. The third microgrid will see that it needs energy if either it's $SOAcc_3^{BAT}$ AND $SOAcc_3^{FT}$ are below $str^{SOAcc_3^{BAT}}_{M\to 3}$ and $str^{SOAcc_3^{FT}}_{M\to 3}$ respectively. The equations are exactly the same as scenario 2 apart from:

$$\begin{aligned} P^{SOAcc_3^{BAT}}_{M\to 3}(t) &= \bigcup_l \left[SOAcc_3^l(t) < str^{SOAcc_3^l}_{M\to 3}(t)\right] \\ E_{3\to N}(t) &= \bigcup_l \left[R^{SOAcc_3^l}_{3\to N}(t) \vee P^{SOAcc_3^l}_{3\to N}(t)\right], \\ &\forall M, \; N\in\{1,2\}, \; M\neq N, \; l\in\{BAT, FT\} \end{aligned} \quad (32)$$

To further investigate various PMSs we allow the PMS^{Hi} to make changes in the local PMSs. More specifically, while in PMS^{Hi}_{1-5} the output of the FC of the 3rd microgrid is $F^{Out,Pow}_{FC\to BAT}(t) = F^{Out,Pow}_{BAT\to LD}(t)$ (as presented in the standalone case, i.e. 1 kW), in PMS^{Hi}_{6-10} we keep the same logical operators as in PMS^{Hi}_{1-5} but the output of the FC is:

$$F^{Out,Pow}_{FC\to BAT}(t) = F^{Out,Pow}_{BAT\to LD}(t) + \sum_{M=1}^{2} E_{M\to 3}(t) F^{Out,Pow}_{M\to 3}(t) \quad (33)$$

This implies that the FC must provide to the 3rd microgrid the extra energy transmitted to the other two microgrids. Furthermore, to implement a PMS whose logical operators, operation of the FC and the power consumed by the EL are time dependant we take into account that during summer (samples [4344,6552]) the main goal is not to reduce the use of the DSL but to transfer energy from microgrids 1 and 2 to the third system in order to be stored as hydrogen in the FT. Hence the new PMSs for $t \in [4344,6552]$ is:

$$\begin{aligned} P^{SOAcc_3^{FT}}_{M\to 3}(t) &= \left[SOAcc_3^{FT}(t) < str^{SOAcc_3^{FT}}_{M\to 3}(t)\right] \\ P^{SOAcc_M^{BAT}}_{M\to 3}(t) &= \left[SOAcc_M^{BAT}(t) > str^{SOAcc_M^{BAT}}_{M\to 3}(t)\right] \\ E_{M\to 3}(t) &= \left[R^{SOAcc_M^{BAT}}_{M\to 3}(t) \vee P^{SOAcc_M^{BAT}}_{M\to 3}(t)\right] \wedge \left[R^{SOAcc_3^{FT}}_{M\to 3}(t) \vee P^{SOAcc_3^{FT}}_{M\to 3}(t)\right], \\ &\forall M\in\{1,2\} \end{aligned} \quad (34)$$

The local changes that should take place at the third microgrid are:

- The FC must remain inactive during the summer months.
- The EL should consume all the energy sent to the third microgrid.

PMS^{Hi}_{11-15} uses these expressions with fixed power delivered from the FC while in PMS^{Hi}_{16-20} we make changes to the local PMS of the third microgrid and the FC delivers power equal to the total load seen by the microgrid.

5.2. Network model

In this case the employed configuration is shown in Fig. 4 which also indicates the binary variables ε that activate each connection. From the diagram it is clear that $\varepsilon_{BAT\to EL} = \varepsilon_{EL\to BF} = \varepsilon_{WT\to EL}$, i.e. when the BAT supplies energy to the EL, so does the WT to the EL and the EL supplies the BF with the produced hydrogen. Similarly $\varepsilon_{BAT\to CMP} = \varepsilon_{CP\to FT} = \varepsilon_{BF\to CMP}$, $\varepsilon_{FT\to FC} = \varepsilon_{FC\to BAT}$.

The input and output flows or signals of each device are vectors as the system has four states. In each case the first entry corresponds to POW, the second to H_2HP, the third to H_2LP and the fourth to H_2O. Hence the output vector of the FC is:

$$F^{Out}_{FC} = \left[\varepsilon_{FC\to BAT}\cdot F^{Out,Pow}_{FC\to BAT} \quad 0 \quad 0 \quad \varepsilon_{FC\to WT}\cdot f^{H_2O}_{FC}\left(F^{Out,Pow}_{FC\to BAT}\right)\right]^T \quad (35)$$

where $F^{Out,Pow}_{FC\to BAT}$ is the power produced by the FC and $f^{H_2O}_{FC}(F^{Out,Pow}_{FC\to BAT})$ is the amount of water that is produced by the FC when its output power is $F^{Out,Pow}_{FC\to BAT}$. Before defining the input to each device, the external inputs to the system are also defined as SF^{Pow}_{PV}, SF^{Pow}_{WG}, SF^{Pow}_{DSL} (determined by local weather conditions and the capacity of the DSL).

The inputs to each specific device may be determined based on the network shown in Fig. 4. The complete list of the output/input vectors is shown in Table 6. The variables ε depend on the operating region of each device, defined in Table 5. The representation of the grid as a network is straightforward (Fig. 5) with the employed variables also shown in Table 5.

6. Results

6.1. Standalone microgrid

In Section 5, five different PMSs were proposed by either changing the length of the hysteresis zones or the conditions for activation of specific connections. The results are summarised in Fig. 6. Regarding the operation of the FC, we can see that the "standard" or "basic" PMS (PMS_1) is the worst as the FC was operated for 1111 h while in PMS_5 where we take into account the energy deficit/surplus is the best regarding the FC with only 92 h of operation in one year.

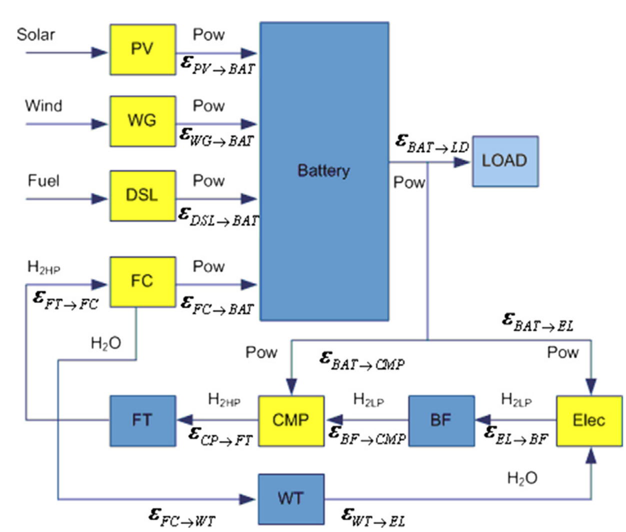

Fig. 4. Network diagram of the standalone microgrid.

Table 5
Operating regions for standalone system and microgrids.

Connection	*str* Value	*stp* Value
PV→BAT	$str_{PV\rightarrow BAT}^{SOAcc^{BAT}} = 90\%$	$stp_{PV\rightarrow BAT}^{SOAcc^{BAT}} = 90\%$
WG→BAT	$str_{WG\rightarrow BAT}^{SOAcc^{BAT}} = 90\%$	$stp_{WG\rightarrow BAT}^{SOAcc^{BAT}} = 90\%$
DSL→BAT	$str_{DSL\rightarrow BAT}^{SOAcc^{BAT}} = 20\%$	$stp_{DSL\rightarrow BAT}^{SOAcc^{BAT}} = 30\%$
FC→BAT	$str_{FC\rightarrow BAT}^{SOAcc^{BAT}} = 31\%$	$stp_{FC\rightarrow BAT}^{SOAcc^{BAT}} = 32\%$
	$str_{FC\rightarrow BAT}^{SOAcc^{FT}} = 10\%$	$stp_{FC\rightarrow BAT}^{SOAcc^{FT}} = 10\%$
	$str_{FC\rightarrow BAT}^{SOAcc^{WT}} = 99\%$	$stp_{FC\rightarrow BAT}^{SOAcc^{WT}} = 99\%$
EL→BF	$str_{EL\rightarrow BF}^{SOAcc^{BAT}} = 69\%$	$stp_{EL\rightarrow BF}^{SOAcc^{BAT}} = 33\%$
	$str_{EL\rightarrow BF}^{SOAcc^{WT}} = 10\%$	$stp_{EL\rightarrow BF}^{SOAcc^{WT}} = 10\%$
	$str_{EL\rightarrow BF}^{SOAcc^{BF}} = 90\%$	$stp_{EL\rightarrow BF}^{SOAcc^{BF}} = 90\%$
CP→FT	$str_{CP\rightarrow FT}^{SOAcc^{BF}} = 7\%$	$stp_{CP\rightarrow FT}^{SOAcc^{BF}} = 29\%$
	$str_{CP\rightarrow FT}^{SOAcc^{FT}} = 90\%$	$stp_{CP\rightarrow FT}^{SOAcc^{FT}} = 90\%$
System 1, $M \in [2,3]$	$str_{M\rightarrow 1}^{SOAcc_1^{BAT}} = 0.3$	–
	$str_{M\rightarrow 1}^{SOAcc_M^{BAT}} = 0.4$	–
	$str_{3\rightarrow 1}^{SOAcc_3^{FT}} = 0.4$	–
System 2, $M \in [1,3]$	$str_{M\rightarrow 2}^{SOAcc_2^{BAT}} = 0.3$	–
	$str_{M\rightarrow 2}^{SOAcc_M^{BAT}} = 0.4$	–
	$str_{3\rightarrow 2}^{SOAcc_3^{FT}} = 0.4$	–
System 3, $M \in [1,2]$	$str_{M\rightarrow 3}^{SOAcc_3^{BAT}} = 0.3$	–
	$str_{M\rightarrow 3}^{SOAcc_M^{BAT}} = 0.4$	–
	$str_{M\rightarrow 3}^{SOAcc_3^{FT}} = 0.2$	–

Table 6
The input and output vectors of each node.

Node	Output vector	
PV	F_{PV}^{Out}	$\left[e_{PV\rightarrow BAT}\cdot f_{PV}^{Pow}(SF_{PV}^{Pow}) \quad 0 \quad 0 \quad 0 \right]^T$
	F_{PV}^{In}	$\left[SF_{PV}^{Pow} \quad 0 \quad 0 \quad 0 \right]^T$
WG	F_{WG}^{Out}	$\left[e_{WG\rightarrow BAT}\cdot f_{WG}^{Pow}(SF_{WG}^{Pow}) \quad 0 \quad 0 \quad 0 \right]^T$
	F_{WG}^{In}	$\left[SF_{WG}^{Pow} \quad 0 \quad 0 \quad 0 \right]^T$
FC	F_{FC}^{Out}	$\left[F_{FC\rightarrow BAT}^{Out,Pow} \quad 0 \quad 0 \quad e_{FC\rightarrow WT}\cdot f_{FC}^{H_2O}(F_{FC\rightarrow BAT}^{Out,Pow}) \right]^T$
	F_{FC}^{In}	$\left[0 \quad \varepsilon_{FT\rightarrow FC}\cdot f_{FT}^{H_2HP}(F_{FC\rightarrow BAT}^{Out,Pow}) \quad 0 \quad 0 \right]^T$
EL	F_{EL}^{Out}	$\left[0 \quad 0 \quad e_{EL\rightarrow BF}\cdot f_{EL}^{H_2LP}(F_{BAT\rightarrow EL}^{Out,Pow}) \quad 0 \right]^T$
	F_{EL}^{In}	$\left[e_{BAT\rightarrow EL}\cdot F_{BAT\rightarrow EL}^{Out,Pow} \quad e_{WT\rightarrow EL}\cdot f_{WT}^{H_2O}(P_{EL}) \quad 0 \quad 0 \right]^T$
CP	F_{CP}^{Out}	$\left[0 \quad e_{CP\rightarrow FT}\cdot f_{CP}^{H_2HP}(F_{BAT\rightarrow CP}^{Out,Pow}) \quad 0 \quad 0 \right]^T$
	F_{CP}^{In}	$\left[0 \quad e_{CP\rightarrow FT}\cdot f_{CP}^{H_2HP}(F_{BAT\rightarrow CP}^{Out,Pow}) \quad 0 \quad 0 \right]^T$
DSL	F_{DSL}^{Out}	$\left[e_{DSL\rightarrow BAT}\cdot f_{DSL}^{Pow}(SF_{DSL}^{Pow}) \quad 0 \quad 0 \quad 0 \right]^T$
	F_{DSL}^{In}	$\left[SF_{DSL}^{Pow} \quad 0 \quad 0 \quad 0 \right]^T$
BAT	F_{BAT}^{Out}	$\left[F_{BAT\rightarrow LD}^{Out,Pow} + \sum_c e_c\cdot F_c^{Out,Pow} \quad 0 \quad 0 \quad 0 \right]^T, \; c\in \left\{ \begin{matrix} BAT\rightarrow EL, \\ BAT\rightarrow CP \end{matrix} \right\}$
	F_{BAT}^{In}	$\left[\sum_c e_c\cdot F_c^{Out,Pow} \quad 0 \quad 0 \quad 0 \right]^T, \; c\in \left\{ \begin{matrix} PV\rightarrow BAT, WG\rightarrow BAT \\ DSL\rightarrow BAT, FC\rightarrow BAT \end{matrix} \right\}$
BF	F_{BF}^{Out}	$\left[0 \quad 0 \quad e_{BF\rightarrow CP}\cdot f_{BF}^{H_2LP}(F_{BAT\rightarrow CP}^{Out,Pow}) \quad 0 \right]^T$
	F_{BF}^{In}	$\left[0 \quad 0 \quad e_{EL\rightarrow BF}\cdot f_{EL}^{H_2LP}(F_{BAT\rightarrow EL}^{Out,Pow}) \quad 0 \right]^T$
FT	F_{FT}^{Out}	$\left[0 \quad e_{FT\rightarrow FC}\cdot f_{FT}^{H_2HP}(F_{FC\rightarrow BAT}^{Out,Pow}) \quad 0 \quad 0 \right]^T$
	F_{FT}^{In}	$\left[0 \quad e_{CP\rightarrow FT}\cdot f_{CP}^{H_2HP}(F_{BAT\rightarrow CP}^{Out,Pow}) \quad 0 \quad 0 \right]^T$
WT	F_{WT}^{Out}	$\left[0 \quad 0 \quad 0 \quad \varepsilon_{FT\rightarrow FC}\cdot f_{FT}^{H_2HP}(F_{FC\rightarrow BAT}^{Out,Pow}) \right]^T$
	F_{WT}^{In}	$\left[0 \quad 0 \quad 0 \quad e_{WT\rightarrow EL}\cdot f_{WT}^{H_2O}(P_{EL}) \right]^T$
LD	F_{LD}^{Out}	$[0 \quad 0 \quad 0 \quad 0]^T$
	F_{LD}^{In}	$\left[F_{BAT\rightarrow LD}^{Out,Pow} \quad 0 \quad 0 \quad 0 \right]^T$

For the operation of the EL the third strategy produces the best results as the connection EL→BF was interrupted 179 times after 3 h of operation. Surprisingly this strategy is also the best regarding the quantity of hydrogen after a year of operation but on the other hand it has wasted a lot of energy from the RESs. Finally, note that the DSL was never activated as the FT was intentionally designed to be large enough and hence store enough hydrogen during the months with high solar radiation.

Among points (a-i,ii) and (b-i,ii) of Section 5.1 considered as decision parameters in the developed PMSs, existing publications mainly account for point (b-ii) or point (b) alone (i.e. not combined with points b-i or b-ii). Although most of the previously published PMSs are less inclusive, their utilisation is of equal importance to the additional PMSs considered in this work. The presented results illustrate that different PMSs have a beneficial effect for particular devices, occasionally at the expense of others. In other words, different PMSs result in trade-offs that provide significant insights for the system operation. The consideration of additional decision options in this work either already captures previously identified insights or introduces previously unexplored operating realisations.

For example in the case of stand-alone systems the 2 previously investigated PMSs [22] consider only $SOAcc^{BAT}$, although BF and FT also accumulate hydrogen. Together with $SOAcc^{BAT}$ they investigate the case that power deficit/surplus is considered as the starting point for the developed *if-else* diagram (in other words only part of point b-ii is considered). This type of PMS is very similar to PMS_5 presented in this work, although PMS_5 is more flexible because it also accounts for the SOAcc of other accumulators except for the battery. Of course, this work considers 4 additional PMSs. As a result, PMS_5 is useful because it reduces the yearly operation of the FC compared to other PMSs, hence prolonging the time for maintenance or replacement. However, PMS_3 which takes into account the length of the hysteresis zone is beneficial for the operation of the EL as well as the utilisation of the stored hydrogen. This is a trade-off revealed due to the presented approach.

By a similar token, paper [43] presents 3 PMSs where point (b-ii) is considered in all cases together with the $SOAcc^{BAT}$ and $SOAcc^{FT}$. In this work such features have been considered in the context of the presented PMSs and their impact on the performance of different devices was highlighted. On top of this, additional features were also considered such as the length of the hysteresis zone, the season with respect to the way energy distribution is managed and the avoidance of point (b-ii). The latter also highlights an important case. It is not necessary to have a PMS that starts by checking the deficit or surplus of power as an initiation point every time. This is omitted in $PMSs_{1\text{-}4}$, resulting in benefits for the operation of different equipment types.

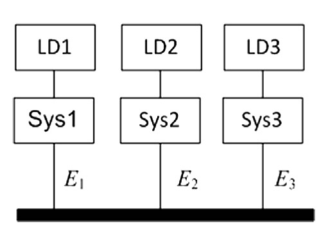

Fig. 5. Grid.

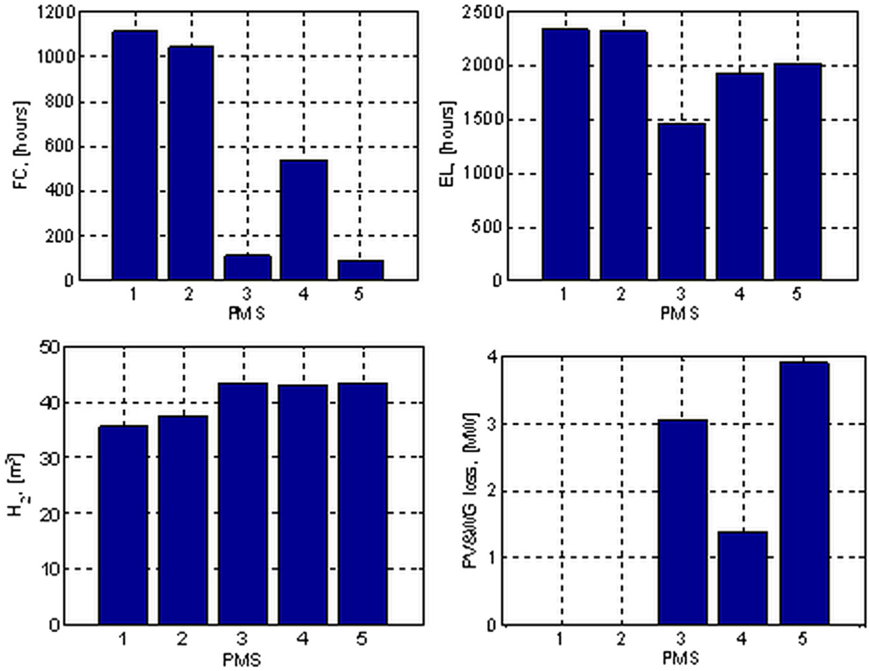

Fig. 6. Results of the standalone system.

6.2. System of microgrids

In this subsection we present the results for the 20 PMSs described in Section 5 (Figs. 7–10). In each case the recorded variables involve: 1) the operation of DSL, FC, EL for each system (in h), 2) the loss of power from PVs and WGs for each system (in W), 3) the change of the $SOAcc_3^{FT}$.

6.2.1. Analysis of PMS_{0-5}^{Hi} (Figs. 7, 8)

When the microgrids are not allowed to exchange energy (PMS 0) i.e. they operate as standalone microgrids, the DSL of the 3rd microgrid is not used as the microgrid is intentionally designed for this, while the DSL of the 2nd microgrid is used for almost 1400 h, this is due to the fact that its battery is small and it has only 100 PV panels. A small usage is recorded for the DSL of the first microgrid. When energy exchange is allowed but by ignoring the FT of the third microgrid we have a big drop in the DSL usage of the 2nd microgrid. However, the DSL of the 1st system is activated more times. This is due to the fact that energy is sent by microgrids 1 and 3 to 2. The DSL of the third microgrid is not activated even if it sends energy to the 1st microgrid as it has many PVs and a FC. Fig. 8 shows the state of accumulation of the three batteries and the energy exchange between the three systems for a particular day (1st of July). It is clear that when the $SOAcc^{BAT}$ of the third system drops below 0.3 and the other two systems have charged batteries, energy will flow from the systems 1 and 2 to the third system.

In PMS 2 when the hydrogen of the third microgrid is taken into account by using the AND as a logical operator both for checking and asking energy, no significant change takes place as the FT is almost full and hence only the state of charge is important. Similar conclusions are also derived for PMS 3, where the third microgrid was checking its energy status by using the OR logical operator but microgrids 1 and 2 checked the available energy in microgrid 3 using AND. We have a significant change in PMSs 4 and 5 as now microgrids 1 and 2 check to see if there is either charged battery or a full FT. As the FT of the 3rd microgrid is full they take energy from that system and hence they do not use their DSL. On the other hand the DSL of the third system is forced to operate many times as its load has significantly increased (due to the power delivery to microgrids 1 and 2) while at the same time its FC supplies only 1 kW.

6.2.2. Analysis of PMS_{6-10}^{Hi} (Fig. 9)

In PMSs 6-10 the FC of the third microgrid is not supplying only 1 kW but it is matching the energy consumed by its load and the energy taken by the other 2 microgrids. This showed a significant improvement in the grid's operation (PMSs 9 and 10). Hence the first step in improving the performance of the grid is to allow for a larger FC and for all systems to check the status of the FT of the third system using the logical operator OR. However there are two extra problems that need to be addressed; all the energy produced by the PVs is not used, while the amount of hydrogen in the FT at the end of the year is less than the initial quantity.

6.2.3. Analysis of PMS_{11-20}^{Hi} (Fig. 10)

By employing the time dependant PMS described in the previous section, the grid's performance is greatly improved, as we still have no use of the DSL but now the wasted energy of the PVs is reduced by 60% while at the same time we have a large surplus of hydrogen (PMSs 11-20).

Hence by using 20 different PMSs the grid's performance can be improved by:

1. Allowing the microgrids to see the FT of the third microgrid and ask for energy if there is either a charged battery or hydrogen in the FT.
2. Forcing the FC to produce more energy and not to operate during summer.
3. Forcing the EL to produce more hydrogen during the summer months.

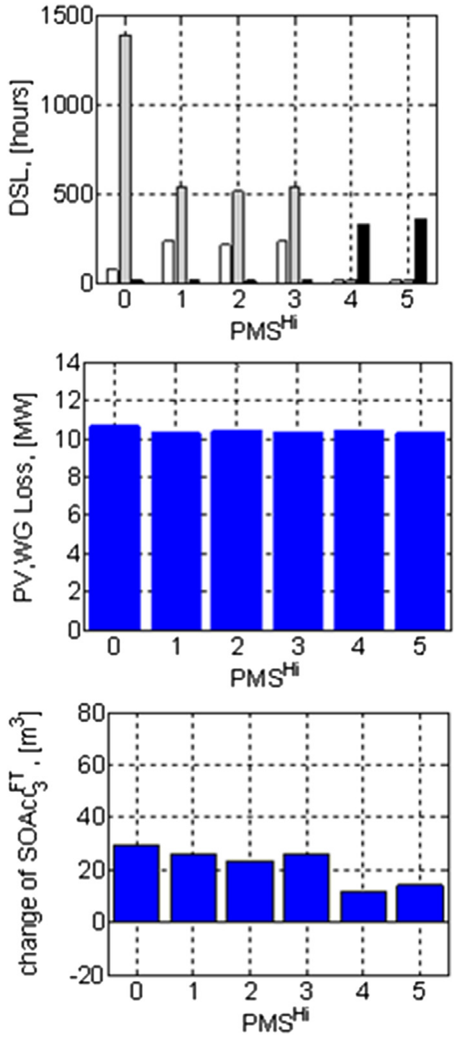

Fig. 7. Operation of the DSL (white bar is for microgrid 1, grey bar is for microgrid 2 and the black bar is for microgrid 3), loss from the RES and the change of the $SOAcc_3^{FT}$ after a year forPMS_{0-5}^{Hi}.

4. Using 2 control strategies, i.e. during the summer the goal is to store as much energy as possible to the FT and during the rest of the year make sure that the DSL in each microgrid is not used.

7. Conclusions

A systemic methodology is proposed in this work that can greatly simplify the representation and implementation of power management strategies of energy systems used in standalone microgrids and systems of microgrids. The new method models in a systematic and efficient way the control laws that govern the system and therefore it allows for more complicated energy management strategies to be adopted. The proposed method has been thoroughly analysed and its effectiveness was demonstrated in standalone and grid applications. The flexibility of the method allowed us to combine and compare several PMSs and obtain the most suitable through a lengthy series of tests. The chosen PMS reduced the usage of FC, EL and DSL, the loss from the RES and maximised the produced hydrogen, hence it greatly improved the grid's behaviour and efficiency. This was achieved as we were able to take into account the state of all energy storage components and to impose several temporal conditions. Similar representation and

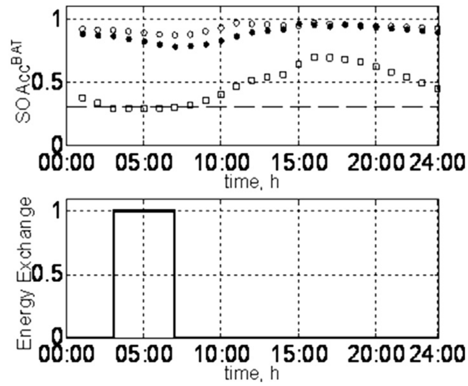

Fig. 8. Energy exchange between the three systems. The solid circles is the $SOAcc^{BAT}$ of the 1st system, the empty circles is the $SOAcc^{BAT}$ of the 2nd system and the squares the $SOAcc^{BAT}$ of the 3rd system that is asking for energy. The dashed line shows the limiting value of 0.3 that is required for a system to ask for energy.

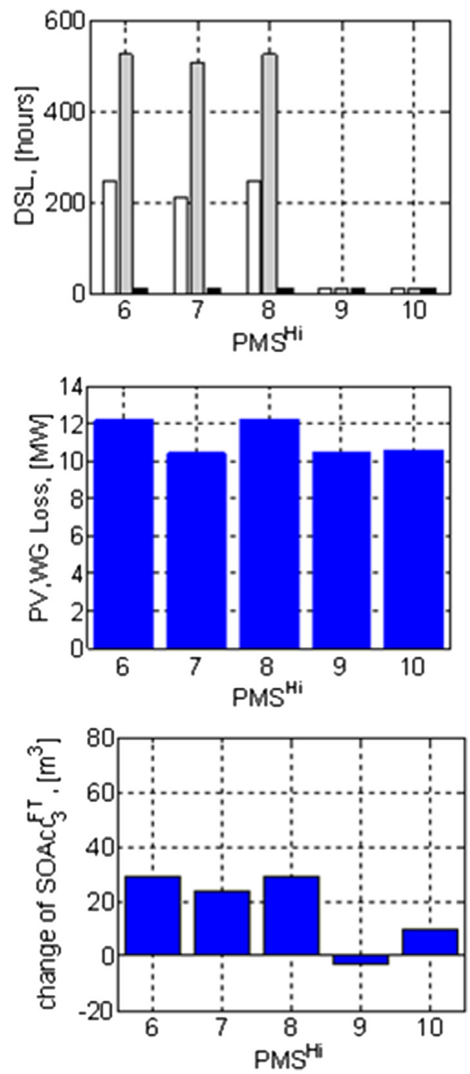

Fig. 9. Operation of the DSL (white bar is for microgrid 1, grey bar is for microgrid 2 and the black bar is for microgrid 3), loss from the RES and the change of the $SOAcc_3^{FT}$ after a year for PMS_{6-10}^{Hi}.

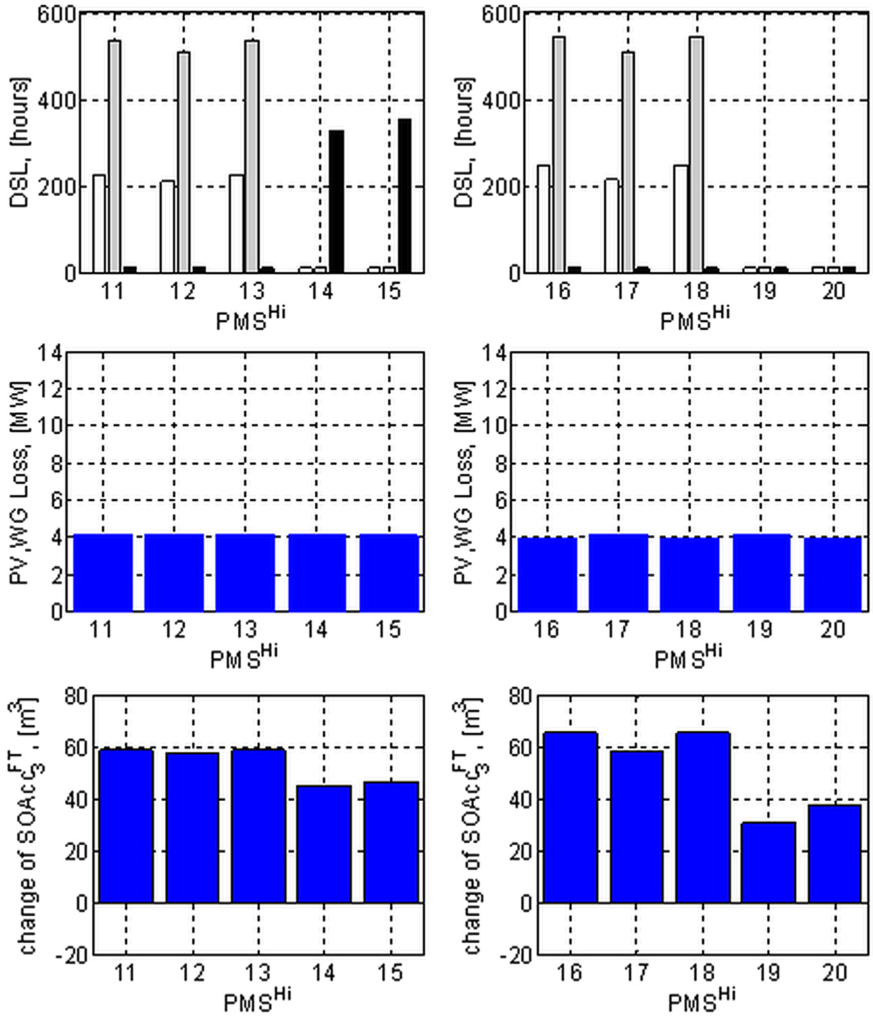

Fig. 10. Operation of the DSL (white bar is for microgrid 1, grey bar is for microgrid 2 and the black bar is for microgrid 3), loss from the RES and the change of the $SOAcc_3^{FT}$ after a year for PMS^{Hi}_{11-20}.

analysis could also contribute in the representation and energy management of a smart grid.

An additional key point here is that these results were easily deduced using the proposed method. Otherwise to implement the aforementioned 20 PMSs using *if-else* statements and every time changing not a single proposal (from AND to OR for example) but a whole branch in the associated flow chart would have been impractical and difficult if more microgrids were employed by the grid. Finally, we need to stress the fact that the models that were used here were validated in Refs. [21–23] and through a detailed error analysis it was found that the models are in good agreement with the experimental results obtained from the actual system in Xanthi, Greece.

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