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A fuzzy logic control of a smart home with energy storage providing active and reactive power flexibility services

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ABSTRACT

There is a need for enhanced flexibility to allow the high penetration of intermittent renewable power into the power system. In this way, transmission system operators (TSO) need more flexible energy resources that help to control the power system frequency by using balancing services. Distribution system operators (DSO) also seek new flexible energy resources that can counteract stochasticity, control voltage level, and manage congestions in distribution networks. Smart homes located in distribution networks are potential resources. Hence, this paper considers a smart home with flexible appliances and devices, including a battery energy storage system (BESS) interfaced with an inverter, an air conditioner (AC), and an electric vehicle (EV). The smart home aims to provide the system operators with coordinated frequency and DSO-level services while respecting the thermal comfort and schedules of the household residence. The inverter-interfaced BESS not only provides active power support for TSO and DSO, but it also injects and consumes reactive power if the DSO needs local flexibility. Fuzzy logic control system is deployed to obtain this goal. In the simulation section, a smart home with flexible appliances is scheduled. Different operations and the economic outcomes are discussed for the smart home considering real-world data.

1. Introduction

1.1. Motivation

Power systems are experiencing tremendous challenges due to the high penetration of intermittent renewable generation, recent electrification in different sectors, and the decentralization of the electricity sector [1,2]. As a result, TSOs need more flexibility to keep the balance between the intermittent generation and the growing uncertain demand. In addition, most fossil fuel-based generators are phasing out in the future, and the TSOs need to deploy new sustainable sources that provide flexibility (ancillary) services [3]. Hence, flexible customers and prosumers have been recently considered as flexible resources that can provide flexibility services such as frequency control-related services for the TSOs [4].

DSOs traditionally employ mechanical devices such as on-load tap changers (OLTCs) and switched capacitors to control network voltage levels and manage congestion in the distribution networks [5,6]. However, the growing number of renewable distributed generation units make these devices unable to follow the fluctuations of voltages rapidly [5]. Thus, DSOs also need additional faster flexible energy resources for this purpose. Smart homes have some flexible appliances whose working time can be scheduled according to the operators' flexibility needs.

Nevertheless, there exists obstacles on the road to smart homes' flexibility provision. First, it needs a cooperative management system that can manage how to provide flexibility for both TSOs and DSOs in a coordinated manner. Besides, the management system needs to know how to utilize appliances in a flexible way while trying not to disturb the comfort and desires of household customers.

1.2. Literature review

In this context, recent research tried to model prosumers or customers providing flexibility services for the system operators. However, some works were only focused on the provision of DSO-level services and disregarded the profits that can be gained from TSO-level services. For instance, [7] modeled a smart home's energy management system that controls EVs and heat pumps to provide DSOs with congestion management services. Reference [8] worked on the flexible operation of shiftable appliances that can be shifted according to the DSO's needs. Reference [9] studied the contribution of smart homes to voltage control

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Nomenclature

Sets

t	Time

Parameters

π_t^{buy}	Price of buying electricity at time t [Cent/kWh]
π_t^{sell}	Price of selling electricity at time t [Cent/kWh]
π_t^{BESS}	Operating cost of using 1 kWh of the BESS capacity at time t [Cent/kWh]
Δt	Scheduling time slot [h]

Variables

P_t^{con}	Active-power output of the inverter at time t [kW]
Q_t^{con}	Reactive-power output of the inverter at time t [kVAR]
$Q_t^{con-FLC}$	Inverter's active power determined by the fuzzy logic controller [kW]
$P_t^{con-FLC}$	Inverter's reactive power determined by the fuzzy logic controller [kVAR]

AC-related parameters

θ^{min}	Lower limit of the indoor temperature of the household [°C]
θ^{max}	Upper limit of the indoor temperature of the household [°C]
θ_t^{a}	Ambient temperature of the household at time t [°C]
α	Constant parameter associated with the thermal characteristic and insulation of the household
β	Coefficient related to the AC's performance [°C /kWh] [heat: $\beta > 0$]
$P^{AC,max}$	Nominal operating power of the AC [kW]

AC-related variables

θ_t^{h}	Indoor temperature of the household at time t [°C]
P_t^{AC}	AC's operating power at time t [kW]

EV-related parameters

$SOC^{EV,min}$	Lower limit of the EV state-of-charge (SOC)
$SOC^{EV,max}$	Upper limit of the EV SOC
Cap^{EV}	Maximum capacity of the EV's battery [kWh]
$P^{EV,max}$	Maximum charging power of the EV [kW]
η^{EV}	Charging efficiency of the EV battery
φ_t	A binary parameter that prevents the EV from being charged when it is unavailable at time t

EV-related variables

SOC_t^{EV}	EV SOC at time t
P_t^{EV}	Charging power of the EV at time t [kW]

BESS-related parameters

$SOC^{BESS,min}$	Lower limit of the BESS SOC at time t
$SOC^{BESS,max}$	Upper limit of the BESS SOC at time t
$P^{dis,max}$	Upper limit of BESS discharging power [kW]
$P^{ch,max}$	Upper limit of BESS charging power [kW]
Cap^{BESS}	Maximum BESS capacity [kWh]
$\eta^{BESS,ch}$	BESS charging efficiency
$\eta^{BESS,dis}$	BES discharging efficiency

BESS-related variables

P_t^{ch}	BESS charging power at time t [kW]
P_t^{dis}	BESS discharging power at time t [kW]
u_t	A binary variable that prevents the BESS from being charged and discharged at the same time

in distribution networks. Authors of [10] proposed a market-based approach for smart homes that contribute to controlling voltage unbalances between the phase voltages in the distribution network. In [11], the energy management system controlled EVs and ACs to compensate for unbalances.

On the other hand, the sole focus of some papers were on the prosumers TSO-level frequency provision. For instance, [12] optimally planned energy communities to provide frequency control services. Reference [11] suggested the contribution of smart homes' heat pumps to frequency control. Authors of [13] modelled aggregated prosumers that provide the TSO with balancing services through developing a mixed-integer linear programming (MILP) problem formulation. Authors of [14] presented an NN-based model in which electric water heaters (EWHs) were scheduled to provide general flexibility services.

There are also some papers proposing the contribution of smart homes to the simultaneous provision of DSO- and TSO-level flexibility services. For example, in [15], authors developed linear programming models for the operation of smart home appliances. The smart home's appliances were scheduled to provide DSO-TSO-level flexibility services. Although the paper suggested that a smart home provides both DSO and TSO with flexibility services, the proposed method was not cooperative. In other words, it did not discuss different situations in which the smart home responds to the system operators' simultaneous needs.

Fuzzy logic rule-based control methods can be deployed in various energy management systems. These controllers can avoid intrinsic nonlinearities and integer involvement when developing devices' scheduling models and therefore, they do not require complex mathematical modeling [16]. There exists several papers proposing energy management systems integrated with fuzzy logic controllers (FLC). For example, [17] integrated the home energy management system (HEMS) with an FLC aiming to decrease the electricity costs of the household. Electricity prices, the inhabitants' presence status, and the solar irradiation were considered inputs of the FLC and the output was the shiftable load's schedule. The work did not consider reactive power flexibility and the focus was not on the flexibility provision for system operators. Reference [16] proposed the utilization of an FLC for the operation of a microgrid depending on the microgrid's components. Authors of [18] developed an FLC for a wind turbine system that can provide frequency control services for the TSO. Reference [19] designed a new FLC-equipped energy management system for a prosumer that have both a roof-mounted solar panel and a wind turbine. The proposed system seeks efficient decisions considering the electricity consumption needs and expenses. Finally, [20] introduced a inverter-interfaced BESS that provides voltage and frequency control services simultaneously. The control of voltage and frequency was done by a novel FLC. However, the work did not specify the type of services and the priority of the service provision. In reality, flexible energy resources can provide different types of frequency control services. Each service needs its own response time and technical characteristics. In addition, the flexibility provider needs to specify its priority in a case where DSO-level signals contradict the TSO-level needs. In these scenarios, if the household provides TSO-level (frequency control) services, the action will adversely affect the secure operation of the distribution network in which the household is located [21].

1.3. Contribution and organization

To compensate the shortcomings of the existing research, this paper develops an energy management system for a smart home equipped with an inverter-interfaced BESS. The smart home only controls its controllable appliances. It provides flexibility services for the local DSO and the TSO in a coordinated manner by utilizing controllable appliances. The

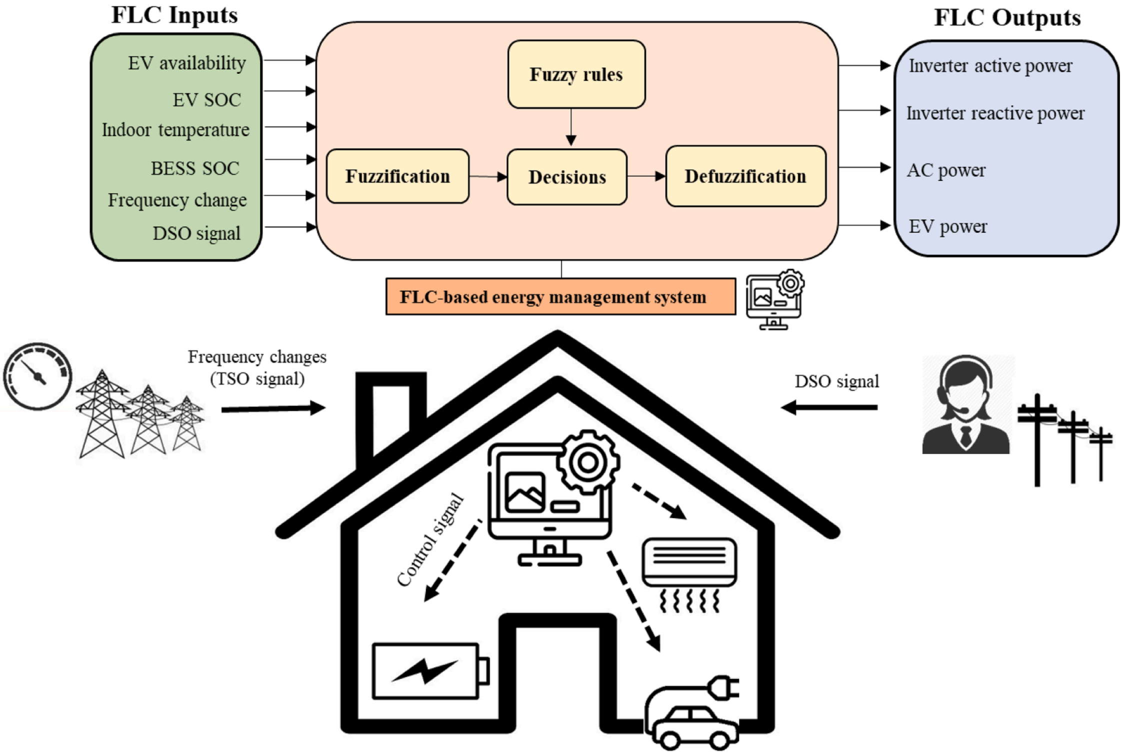


Fig. 1. The proposed FLC-based energy management system.

proposed energy management system utilizes a fuzzy logic control method, as follows:

- The smart home provides frequency containment reserves for normal operation (FCR-N) and offers flexibility services for the local DSO simultaneously. In cases where TSO's and DSO's needs contradict each other, the smart home gives priority to the flexibility provision of the local DSO. Otherwise, it might jeopardize the electricity supply quality of the local distribution network, where the smart home is located [21]. The frequency regulation services are provided by active power (P) flexibility while the DSO-level flexibility is provided by both active (P) and reactive power (Q) flexibility.
- An FLC with the minimum number of rules is designed. The objective is to provide flexibility through managing the operation of household appliances including the temperature-dependent AC, the charging timetable of the EV, as well as the active and reactive power extracted from the inverter-interfaced BESS. Although they are reacting to the flexibility signals, the appliances' operational constraints are fully respected.
- Fuzzy logic rules are defined in a way to prioritize must-run appliances in providing flexibility. They propose not to utilize the BESS much due to its operating costs unless the DSO needs high flexibility.

Also, three different cases, called price-based and self-sufficient cases, are developed to see how the household appliances react in different situations if the household is just subjected to the day-ahead market prices. Finally, it is assessed whether flexibility provision is economically efficient for the household or not, using real-world data from Finnish FCR-N and frequency open database [22].

The rest of the paper is organized as follows. Section 3 discusses the provision of DSO-TSO flexibility services. Section 4 introduces the FLC design. Section 5 develops other cases for further comparisons. Section 6 implements the control method and discusses the results. Finally, section 7 concludes the paper.

2. Active and reactive power flexibility provision by smart homes

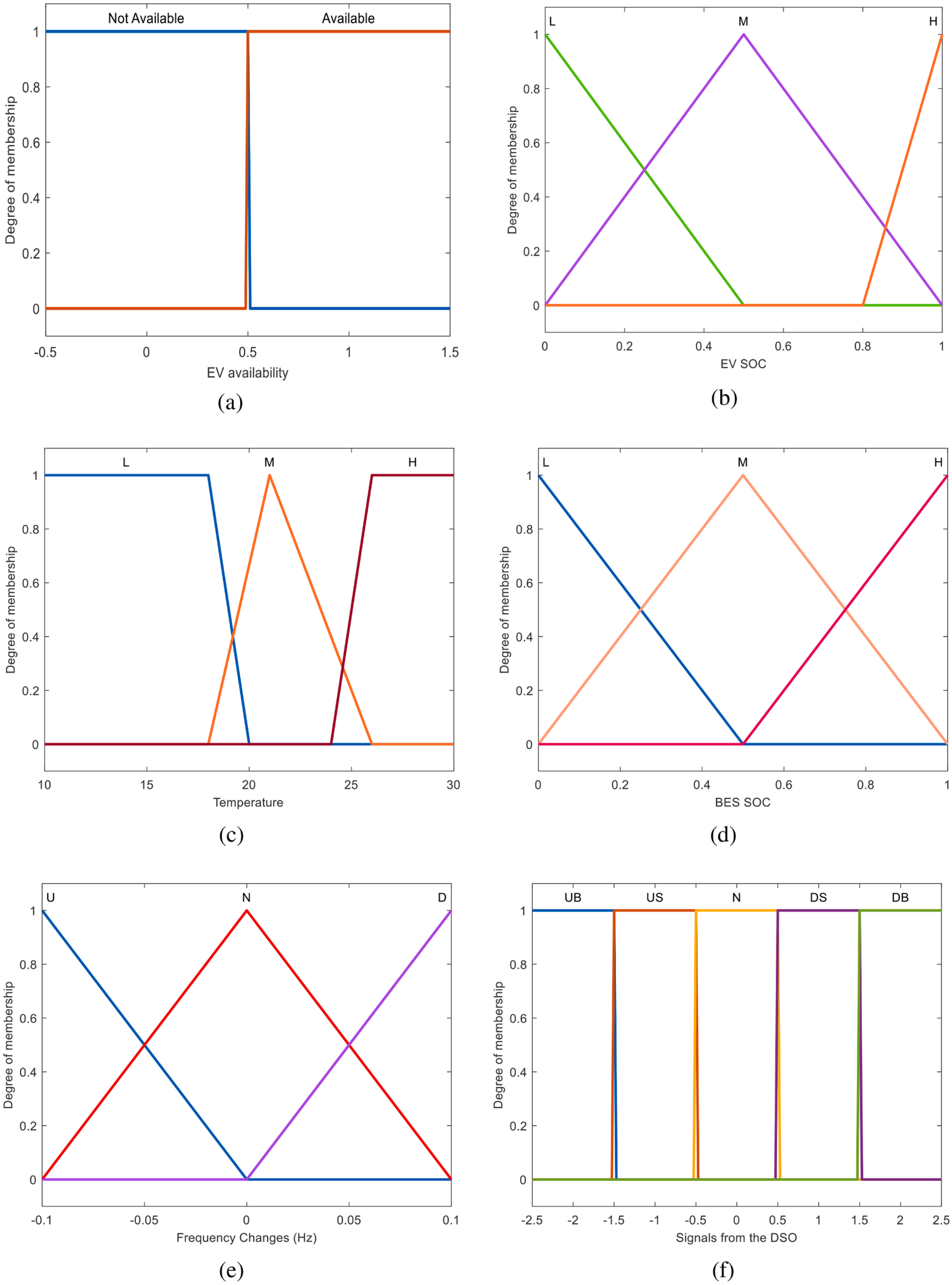
2.1. Frequency control and DSO-level flexibility

The smart home is assumed to provide DSO-level services which are in a form of "upward" or "downward" flexibility services. The DSO first runs an optimal power flow (OPF) calculation for the distribution network and then it might need the consumers and prosumers at some specific nodes to change their consumption or production/generation. In this way, the DSO will be able to manage congestion and voltages in the network. When the DSO needs upward flexibility it sends a signal to smart homes to increase their generation (if possible) or decrease their consumption. Otherwise, if it needs downward flexibility, it asks smart homes to increase their consumption or decrease their generation. The smart home is assumed to react to this flexibility signal by controlling the active power consumed by appliances as well as active and reactive power produced/consumed by the inverter-interfaced BESS.

On the other hand, the smart home is assumed to provide FCR-N service for the TSO. The provision of FCR-N service is based on local frequency measurement. In this way, the smart home reacts to the frequency when it varies in the range of 49.9-50.1 Hz [23–25]. When the frequency falls below 50 Hz to 49.9 Hz, the smart home decreases its consumption or increases discharging i.e. active power produced by its inverter-interfaced BESS. In cases where the frequency goes beyond 50 Hz, until 50.1 Hz, the smart home increases its consumption and charges the BESS. FCR-N was selected among frequency services since it is one of the most expensive services and the smart home can accordingly receive higher profits if it provides this frequency regulation service [26].

2.2. Inverter-based resource flexibility provision

This research is based on the assumption that a smart-home will have power electronics flexibilities, based on multifunctional inverters, capable to provide both active and reactive for the DSO. The reactive power services are provided by real-time control using d-q and p-q



(a) (b) (c) (d) (e) (f)

Fig. 2. Membership functions (MF) of the input variables: (a) MFs of EV availability, (b) MFs of EV SOC, (c) MFs of temperature, (d) MFs of BES SOC, (e) MFs of frequency changes, (f) MFs of DSO's flexibility signals.

instantaneous power theory based control for the inverter. The package is sometimes defined as a converter referring to the power electronic interfacing from the energy source (the BESS in this case) connected to the point of common coupling at the utility grid. In addition, since the BESS' output is DC, an AC/DC-inverter is used to connect it to the AC grid. We also assume that the inverter has the capability to control both consumed/produced active and reactive power in their acceptable ranges. The AC-DC inverter is considered to have oversizing option with the oversizing factor, *OSF*. Thus, the following constraint should be taken into account for the inverter:

$$P_t^2 + Q_t^2 \leq (1 + OSF\ S^{max})^2 \tag{1}$$

Where S^{max} is the inverter's rated capacity, P_t is its active power produced/consumed while Q_t is the inverter's reactive power produced/

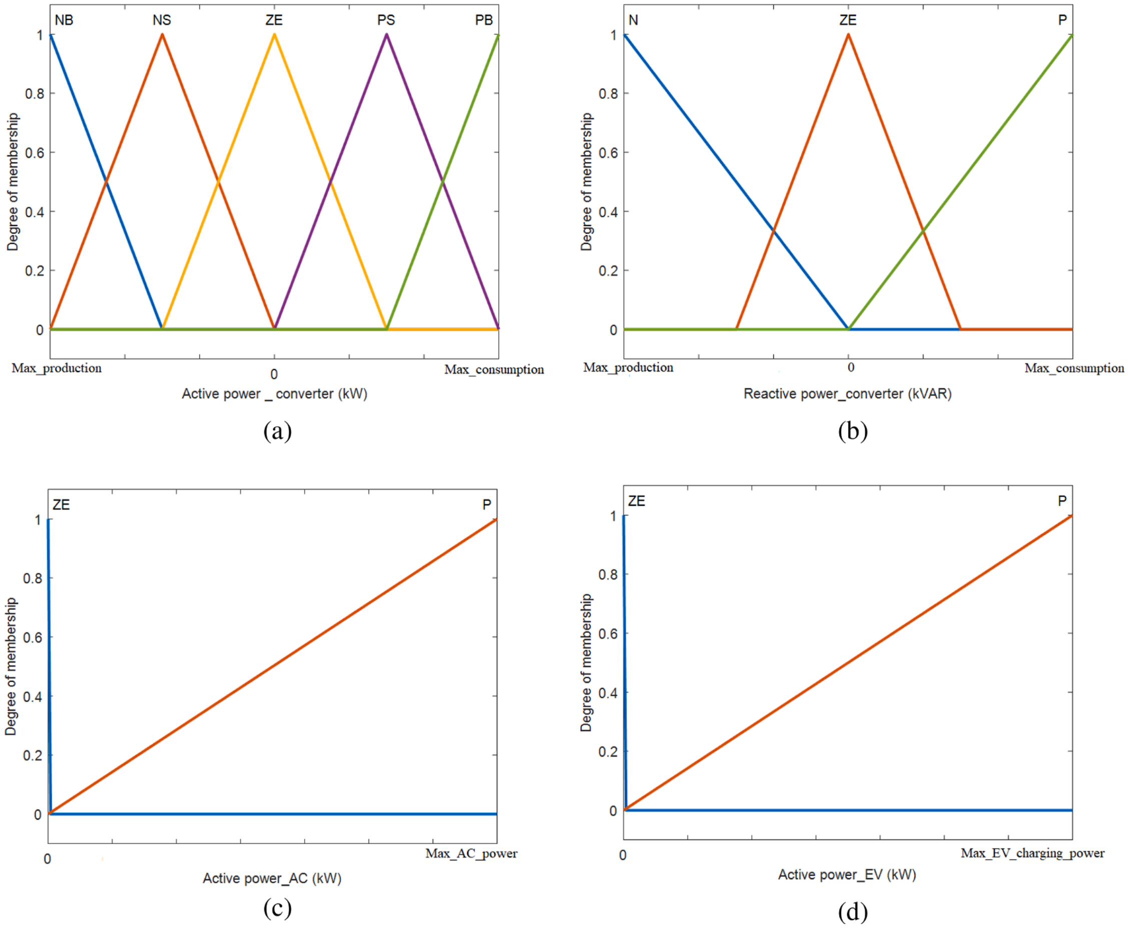


Fig. 3. Membership functions (MF) of the output variables: (a) MFs of inverter's active power output, (b) MFs of inverter's reactive power output, (c) MFs of AC consumption, (d) MFs of EV charging consumption.

consumed. With the help of constraint (1), the maximum reactive power i.e. Q^{con_max} can be obtained.

The output active and reactive power need to be modified after they are determined by the FLC [20]. The output is obtained as follows [20]:

$$P_t^{con} = P_t^{con-FLC} \tag{2}$$

$$Q_t^{con} = \frac{\left|Q_t^{con-FLC}\right|}{Q_t^{con-FLC}} \min\left(Q^{con\_max}, \left|Q_t^{con-FLC}\right|\right) \tag{3}$$

In (2), P_t^{con} is the output active power of the inverter which is determined by the FLC's output, i.e. $P_t^{con-FLC}$. However, (3) determines the output reactive power of the inverter, Q_t^{con}. In (3), $Q_t^{con-FLC}$ is the reactive power obtained by the proposed FLC. The proposed FLC will be described in the next section.

3. Proposed fuzzy logic-based coordinated control

The paper presents a Mamdani Fuzzy Interface System (FIS) which includes three main parts. A fuzzier converts the inputs' crisp values to fuzzy values. Fuzzy rules determine how the outputs are obtained based on the inputs' fuzzy values. A defuzzifier converts back the outputs' fuzzy values to the crisp values [27]. Finally, the inverter's outputs are determined using (2) and (3). Fig. 1 explains how the proposed energy management system works and illustrates the inputs and outputs of the system.

The proposed FLC is able to coordinate active and reactive power with the operators' flexibility needs. In distribution networks, the ratio of lines' reactance to their resistance is low [28]. Thus, active power can be utilized besides reactive power to control voltages in these networks. In other words, DSOs can employ both active and reactive power services to manage the network. Active power also influences system frequency. The TSO uses active power services to control frequency in real-time. Hence, there might exist situations in which the active power provided for frequency control worsen the voltage situations at some nodes or causes congestion in the local distribution network [29, 30]. In order to avoid this situation, fuzzy rules should define different situations and determine the controller's reaction.

3.1. Fuzzy logic controller design

An FLC was designed with aim of coordinating active and reactive power flexibility of controllable appliances for TSO-DSO flexibility needs. This FLC accepts six inputs. The inputs consist of 1) EV pre-schedules (EV availability), 2) EV state-of-charge (SOC), 3) indoor temperature, 4) BESS SOC 4) measured frequency, and 5) flexibility signal from the DSO. The inputs' crisp values have been fuzzified via membership functions before they are sent to the FLC.

3.1.1. Membership functions of inputs

Fig. 2 depicts the membership functions that are defined for each input. In this paper, the membership functions of inputs and outputs are mostly defined using Interval Estimation (IS) method. IS method aims to introduce an interval that describes the access of a value of the variable in the best way [31]. As the EV availability membership functions state, an EV is either available or unavailable to be charged. We defined some values that describe the available EV and some others that indicate the unavailable EV. The availability is determined based on the owner's

Table 1

Rules related to the active power output of the inverter-interfaced BESS.

#	BESS SOC	Frequency changes	DSO signal	Inverter active power	Designed according to
1	M	D	N	PS	d
2	H	D	N	ZE	MR
3	L	D	N	PB	a
4	M	N	N	ZE	h
5	H	N	N	NS	b
6	L	N	N	PS	a
7	M	U	N	NS	d
8	H	U	N	NB	b
9	L	U	N	ZE	MR
10	L	N	DB	PB	a
11	M	N	DB	PS	e
12	H	N	DB	ZE	MR
13	L	N	DS	PS	a
14	M	N	DS	ZE	c
15	H	N	DS	ZE	MR
16	L	N	UB	ZE	MR
17	M	N	UB	NB	e
18	H	N	UB	NB	b, e
19	L	N	US	ZE	MR
20	M	N	US	ZE	c
21	H	N	US	NB	b
22	-	D	US	ZE	f
23	-	D	UB	ZE	f
24	-	U	DS	ZE	f
25	-	U	DB	ZE	f
26	L	U	US	ZE	MR
27	M	U	US	NB	g
28	H	U	US	NB	g
29	L	U	UB	ZE	MR
30	M	U	UB	NB	g
31	H	U	UB	NB	g
32	L	D	DS	PB	g
33	M	D	DS	PB	g
34	H	D	DS	ZE	MR
35	L	D	DB	PB	g
36	M	D	DB	PB	g
37	H	D	DB	ZE	MR

preschedule. The membership functions of EV SOC as well as those of the BESS SOC are defined to have three ranges, low (L), medium (M), and high (H). The BESS membership functions are adopted from [20], while those of EV can be determined by the customers, using IS method. The customers determine what the high EV SOC is meant to them or to what degree each EV SOC is high, medium, or low. In this paper, the high (H) EV SOC starts from 80% and reaches its maximum in 100% as the figure states. The temperature membership functions are defined according to the standards defined by The Finnish Ministry of Social Affairs and Health's Housing Health Guide for the indoor air temperature [32]. This the temperatures lower than 18 °C and higher than 26 °C are considered to be low (L) and (H), respectively and they are not acceptable.

The energy management system receives two external signals from TSO and DSO. TSO-related signal measures frequency changes and indicates whether the TSO needs flexibility. The membership functions of frequency changes are defined to be upward (U), Downward (D), or None (N). If the frequency changes have negative values, the TSO needs upward flexibility (U). On the other hand, if the frequency changes are positive, the TSO needs more downward flexibility (D). If the frequency change shows N, it means that the household does not need to change its behavior.

The last membership functions depict the DSO's flexibility needs whose signals are sent to the household energy management system. First, the DSO runs an optimal power flow on their system. Then, it sends a flexibility signal, if it needs the flexibility of the household. The flexibility signal can be (UB, US, N, DS, DB). UB is sent when the DSO requires big upward flexibility and US shows small upward flexibility need. N means that the DSO does not need flexibility. On the other hand, DS and DB stand for downward small and big flexibility needs, respectively.

3.1.2. *Membership functions of outputs*

The FLC then gives four outputs, including active and reactive power of the AC-DC inverter, $(P_t^{con-FLC})$, $(Q_t^{con-FLC})$, the active power consumed by the AC as well as the EV charging power. The membership functions of the outputs are illustrated in Fig. 3.

Membership functions are defined based on the characteristic of the outputs. Active and reactive power of the BESS can have positive and negative values. Positive values indicate the consumption whereas negative values state that the device produces power. The inverter's output can be negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB), in terms of active power. The inverter's reactive power can be negative (N), zero (ZE), and positive (P). AC power is considered in the range of 0 to its maximum nominal power in kW. The AC can be either OFF with zero output (ZE) or ON with positive (P) active power consumption. Similarly, the EV charging power can have a zero (ZE) value or a positive (P) value. The charging power varies from 0 to its nominal power in kW. Again, IS method is adopted to determine the outputs' membership functions.

3.1.3. *Fuzzy rules*

Fuzzy Rules describe the relationship between input values and output values. A fuzzy logic-based controller is a decision-making system that defines appropriate output for a certain combination of inputs, based on a set of rules defined by heuristics and in-depth understanding of the functionalities of the overall system. A Fuzzy logic-based controller can also provide adaptively decreasing step sizes when it searches for the optimum point which leads to the fast convergence [33]. Here, the DSO is assumed to have five different flexibility needs whereas the TSO can have three of them. Rules specify how to come up with the decisions in different combinations of inputs.

The rules that are defined for each appliance are supposed to manage critical situations with counteracting services. Regarding the inverter-interfaced BESS, the active power equals zero when the DSO's and TSO's flexibility needs do not have the same direction. In these situations, the inverter reacts to the DSO signal by changing its reactive power rather than active power. On the other hand, must-run appliances that do not have reactive-power-control capability, give priority to the DSO's needs and respond to the DSO's signals in counteracting situations. The DSO mostly requires services that should be provided by specific nodes within local networks whereas TSO's frequency services can be provided by a number of resources in different regions and voltage levels. In another word, local flexible resources are more important to the local DSO than the TSO, and the smart home, as a local resource, has more impact on the flexibility of local networks. Accordingly, the rules are defined in a way that the smart home prioritizes DSO's flexibility needs in situations where TSO's and DSO's needs contradict each other.

Table 1 describes the rules associated with the active-reactive power output of the inverter-interfaced BESS. The following principles help to design the rules:

Meta Rule (MR): It includes the main rules of the system which should be respected in all situations. This is the rule associated with the BESS's operational constraints and prevents the BESS from high degradation costs. According to the MR, a BESS must not be charged if its SOC is high (H), and it must not be discharged if the BESS SOC is low (L). The other rules are as follows:

a) If the SOC is low (L), the active power tends to become positive values (PB, PS) in order to reach its medium (M) level. This is because the BESS with medium SOC is able to provide more flexibility in both directions. This benefits both DSO and TSO in their real-time operations.

Table 2
Rules related to the reactive power output of the inverter-interfaced BESS.

#	DSO signal	Inverter reactive power
38	UB	N
39	US	N
40	N	ZE
41	DS	P
42	DB	P

Table 3
Rules related to the AC output.

#	Temperature	Frequency changes	DSO signal	AC output	Designed according to
43	L	-	-	P	MR
44	H	-	-	ZE	MR
45	M	N	N	ZE	d
46	M	U	N	ZE	c
47	M	D	N	P	c
48	M	-	DB	P	a, (b)
49	M	-	DS	P	a, (b)
50	M	-	UB	ZE	a, (b)
51	M	-	US	ZE	a, (b)

Table 4
Rules related to the EV charging output.

#	EV availability	EV SOC	Frequency changes	DSO signal	EV output	Designed according to
52	Not Available	-	-	-	ZE	MR
53	Available	H	-	-	ZE	MR
54	Available	-	N	N	ZE	d
55	Available	L	D	N	P	a
56	Available	M	D	N	P	a
57	Available	L	U	N	ZE	a
58	Available	M	U	N	ZE	a
59	Available	-	-	US	ZE	b, (c)
60	Available	-	-	UB	ZE	b, (c)
61	Available	L	-	DB	P	b, (c)
62	Available	M	-	DB	P	b, (c)
63	Available	L	-	DS	P	b, (c)
64	Available	M	-	DS	P	b, (c)

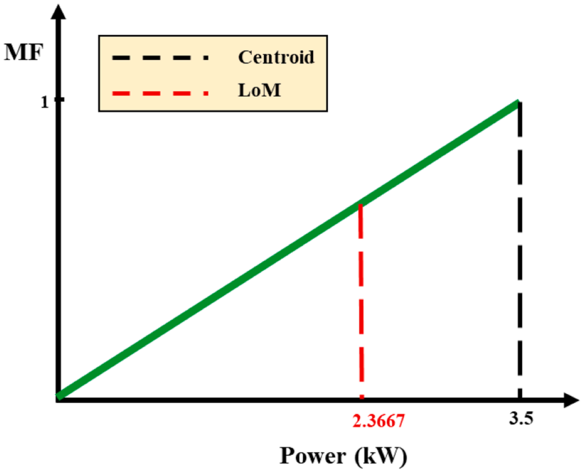


Fig. 4. Centroid vs. LoM defuzzification method.

b) If the SOC is high (H), the active power tends towards negative values (NB, NS) to approach the medium (M) level.
c) The BESS' active power does not react to the DSO's small flexibility needs (US and DS) and lets other must-run appliances react to these needs. Must-run appliances are those that must be operated during a specific time period. In this case, EV and AC are must-run appliances. Thus, it is more cost-efficient to use only must-run appliances' flexibility in non-emergency situations.
d) It reacts weakly (with PS and NS), in response to the positive and negative frequency changes, respectively.
e) It reacts strongly (with PB and NB), if the DSO needs higher flexibility (UB, DB).
f) It equals zero when the DSO's and TSO's flexibility needs do not have the same direction. In these situations, the inverter reacts to the DSO signal by changing its reactive power rather than active power.
g) It responds strongly (with PB and NB) if DSO's and TSO's needs have the same direction.
h) It does not react if the DSO and the TSO do not require flexibility.

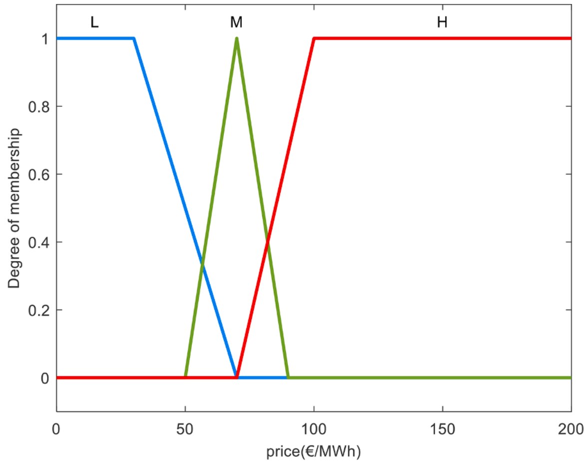


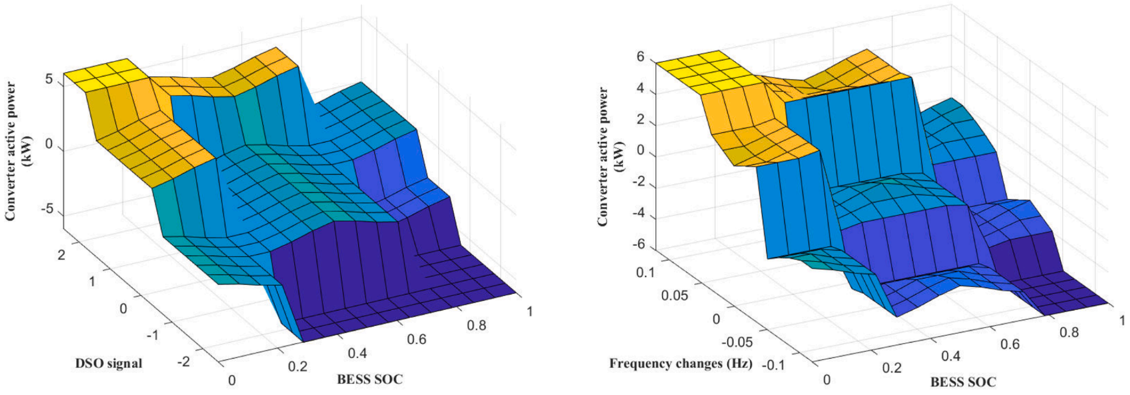
Fig. 5. Membership functions of the energy day-ahead price

The reactive power output of the inverter-interfaced BESS only responds to the DSO's needs. It equals a positive value when the DSO requires downward flexibility while it is negative in response to the DSO's upward needs. Table 2 illustrates the related rules.

In general, the AC's output power is set according to the real-time measured indoor temperature. However, AC's flexible operation is possible if it does not disturb the thermal comfort of the occupants. Thus, the Meta rule (MR) is that the AC must not react to the flexibility signals if the temperature is low (L) or high (H). It is because AC's first job is to maintain the temperature within the comfortable range. Other rules are applied based on the following rules and indicated in Table 3.

a) It completely reacts to the DSO's flexibility signals, by switching off the AC when it needs upward flexibility and turning on the AC in case the DSO requires downward flexibility.
b) It gives priority to the DSO's needs and responds to the DSO's signals even if DSO's and TSO's signals do not have the same direction.
c) It also responds to the frequency changes (TSO needs) if they do not contradict the DSO's requirements.
d) The AC does not respond if the DSO and the TSO do not require flexibility.

Similar to the AC, EV's priority is to fulfill DSO's flexibility needs. However, the EV should be charged in predefined time periods that were defined by the owner. This schedule is modeled by availability signals. Two Meta rules (MR) exist here. First, the EV is allowed to be charged if it is available. Second, the EV is not charged if its SOC is high (H). Table 4 describes the rules for EV charging. In general, the following rules are applied to EV charging, if the EV SOC is either low (L) or medium (M):



(a) (b)

Fig. 6. Inverter's output in terms of flexibility signals ((a) DSO signals, (b) frequency changes) and BESS SOC.

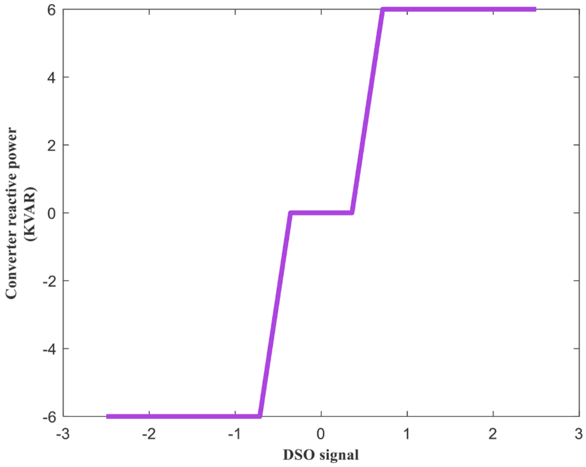


Fig. 7. BESS inverter's reactive power in response to the DSO's flexibility signals.

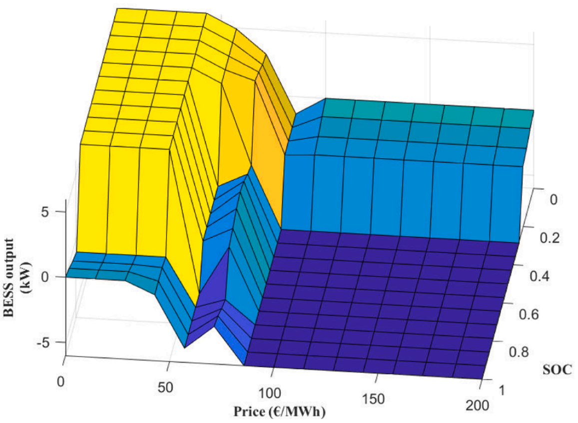


Fig. 8. BESS inverter's active power in response to the price signals.

a) The EV reacts to the frequency changes if its direction is not apposite of the DSO's need.
b) It completely reacts to DSO's flexibility signals.
c) It prioritizes DSO's needs if the DSO and the TSO require different flexibility signals.
d) It does not react if the DSO and the TSO do not require flexibility.

3.1.4. *Defuzzification method*

The Largest of Maximum (LoM) method is deployed to obtain the outputs' crisp values. This method gives the largest value for which the output fuzzy set is maximum. The LoM defuzzification method is proposed because we are more interested in obtaining the maximum output of each flexible appliance in response to the flexibility signals. Fig. 4 compares the crisp values yield by LoM and Centroid defuzzification methods, considering a linear membership function with 3.5 kW maximum output, such as the one associated with the AC output. Although the centroid method was adopted by most of the previous literature such as [20], it does not lead to the maximum output in Fig. 4. In our scheduling problem, it is more economical to extract the maximum output since the flexibility provided by appliances is going to be remunerated by the TSO and the DSO. Thus, LoM is more suitable especially for scheduling EVs and ACs that have similar member functions as shown by Fig. 3.

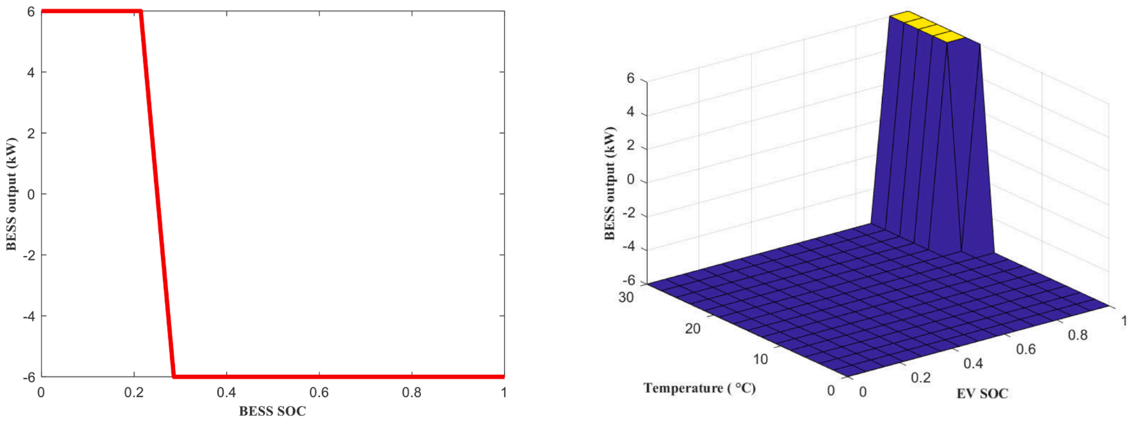
3.2. *Development of further Case studies*

Three more FLC-based models are also developed in order to be compared with our proposed model. The FCL-based cases are developed using Fuzzy Logic Toolbox in Matlab [34] while the optimization problem is solved by CVXPY in Python [35]. These cases are described in the following:

3.2.1. *Fuzzy logic price based model*

Price-based models aim to maximize the financial profits of the household and minimize its energy costs. References [36] and [37] are two examples of price-based models. The models consider that the household is subjected to hourly energy market prices as some retailers such as Finnish retailers give this option to their customers [36]. The price-based models are developed using an FLC and an optimization problem. The FLC-equipped price-based model tries to minimize energy costs in real time. When the price is low (L), the household consumes more energy which means that the BESS is charged and the other appliances are switched on as much as possible. When the price is high (H), the household consumes less and produces more. It means that the BESS is discharged, and other appliances are scheduled to consume less possible energy.

Regarding the FLC-equipped price-based model, it has five inputs including the EV availability and the EV SOC, the temperature, the BESS SOC, and the price. The membership functions of common inputs are the same as those of the proposed model. The membership functions of the price can be designed based on the definition of low (L), medium (M), and high (H) prices. This definition should consider the operational costs of household devices such as BESS operating costs. The prices of buying electricity might be different from the prices of selling electricity. In this



(a) (b)

Fig. 9. BESS active power output (a): based on its own BESS (b) based on the EV SOC and the indoor temperature.

situation, both buying and selling prices should be added as the inputs. Fig. 5 depicts the prices' membership functions considered in this paper for both buying and selling prices. The outputs of this model are the active-power outputs of the BESS, the EV, and the AC. They have the same membership functions as shown in Fig. 3. Reactive power is disregarded in this model since the authors did not find implemented dynamic pricing for active power in a real-world system.

3.2.2. Price-based model with optimization

The price-based model can be also developed in a form of an optimization problem. This optimization problem aims to minimize household electricity costs on a day-ahead basis. Mathematically, the problem can be written as follows [18,38]:

$$\min_{P_t^{ch},\, P_t^{dis}, P_t^{EV}, P_t^{AC}} \sum_{t=1}^{24} \underbrace{\pi_t^{buy}\left(P_t^{ch} + P_t^{EV} + P_t^{AC}\right)}_{Cost\ I} - \underbrace{\pi_t^{sell}\left(P_t^{dis}\right)}_{Revenue} + \underbrace{\pi^{BESS}\left(P_t^{ch} + P_t^{dis}\right)}_{Cost\ II} \tag{4}$$

subject to:

$$\theta_t^h = (1-\alpha)\theta_{t-1}^h + \alpha\theta_t^a + \beta P_t^{AC}\Delta t \tag{5}$$

$$\theta^{min} \le \theta_t^h \le \theta^{max} \tag{6}$$

$$0 \le P_t^{AC} \le P^{AC,max} \tag{7}$$

$$0 \le P_t^{EV} \le \varphi_t P^{EV,max} \tag{8}$$

$$SOC_t^{EV} = SOC_{t-1}^{EV} + \frac{\eta^{EV} P_t^{EV} \Delta t}{Cap^{EV}} \tag{9}$$

$$SOC^{EV,min} \le SOC_t^{EV} \le SOC^{EV,max} \tag{10}$$

$$0 \le P_t^{dis} \le u_t P^{dis,max} \tag{11}$$

$$0 \le P_t^{ch} \le (1-u_t) P^{ch,max} \tag{12}$$

$$SOC_t^{BESS} = SOC_{t-1}^{BESS} + \frac{\eta^{BESS,ch} P_t^{ch} \Delta t - \eta^{BESS,dis} P_t^{dis} \Delta t}{Cap^{BESS}} \tag{13}$$

$$SOC^{BESS,min} \le SOC_t^{BESS} \le SOC^{BESS,max} \tag{14}$$

Where (4) denotes the objective function and (5)-(14) are the constraints that restrict the objective function. The objective function consists of *Cost I*, the total cost of electricity consumption, *Cost II*, the operating cost of the BESS, and *Revenue* representing the revenue obtained from selling electricity production. BESS operating cost can be estimated using the method proposed by [39]. Eq. (5) relates AC outputs to the indoor temperatures; (6) is the constraint associated with the indoor temperature; and (7) keeps the working power of the AC within its permissible range. In addition, (8)-(10) denote EV's operational constraints. Constraint (8) checks whether EV's charging power is within the allowable range, (9) relates the EV SOC to the charging power and (10) maintains the EV SOC within the defined range. Similarly, (11) and (12) impose constraints on the charging and discharging power of the BESS, (13) explain the mathematical relationship between the BESS SOC and its charging and discharging power. Finally, (14) denotes the upper and the lower limits of the BESS SOC.

3.2.3. Self-sufficient model

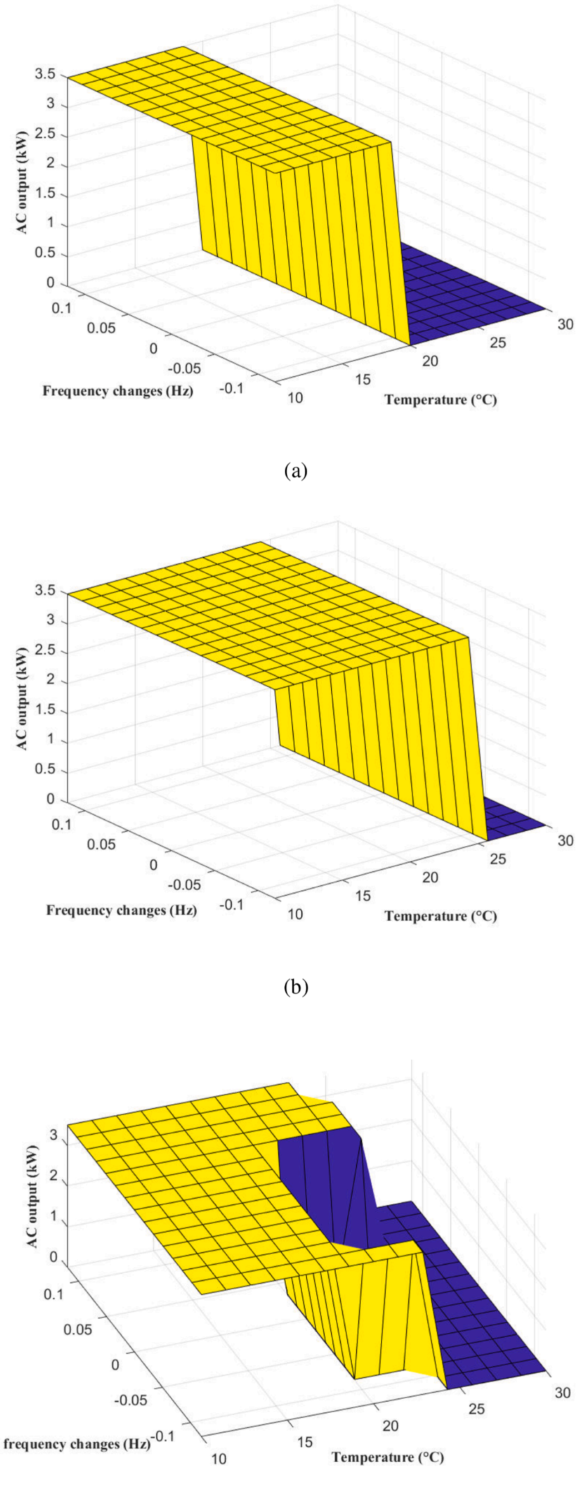
The self-sufficient model represents a scenario in which the household tries to increase their self-sufficiency by supplying the EV and the AC with its own BESS as much as possible. Reference [40] is an example trying to maximize the self-sufficiency of smart homes by managing appliances and flexible resource. In this case, the following rules are applied to the FLC-based management system:

Meta rules (MR): These rules aim to maintain the constraints that are embedded in appliances' characteristics or directly affect the occupants' comfort. The rules state that the AC should be ON when the temperature is low (L) and should be turned off if the temperature is high (H) or medium (M). Besides, the EV cannot be charged when it is not available and when the EV SOC is high (H).

a) The household is assumed to charge the BESS whenever the SOC is low (L).
b) In medium-BESS-SOC situations, it charges the BESS if the EV and the AC do not need to consume power.
c) The household discharges the BESS when the EV or/and the SOC consume electricity and the BESS SOC is either high (H) or medium (M).
d) The BESS is not charged or discharged, when the BESS SOC is high (H) and the EV and AC are not working.
e) EV is charged when it is available, the BESS SOC is not low (L), and the AC is not working.

4. Simulation results and case study

The proposed fuzzy-logic controller was designed using the Fuzzy Logic Toolbox in Matlab [34]. The rule-based Madani fuzzy logic interface system was developed for scheduling 3.5 kW AC, an EV with 8 kW charging power and also a BESS with 6 kW charging and discharging power and 14 kWh capacity.



(a)

(b)

(c)

Fig. 10. AC output in response to frequency changes when the DSO needs (a) upward flexibility (b) downward flexibility (c) no flexibility.

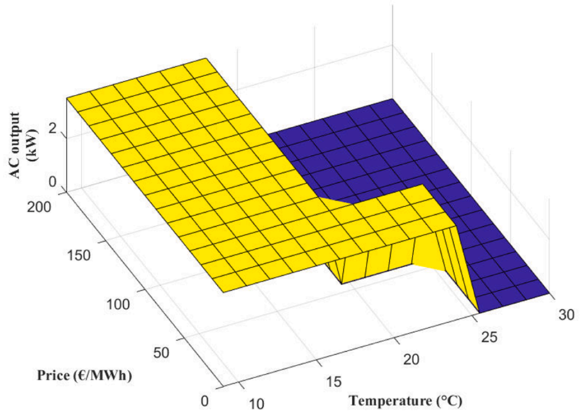


Fig. 11. AC output in response to the price signals.

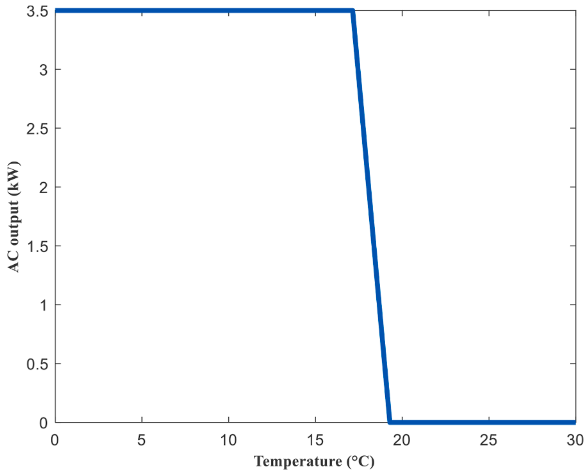


Fig. 12. AC output in the self-sufficient model.

4.1. *Operations of flexible devices*

4.1.1. *Inverter-interfaced BESS operation*

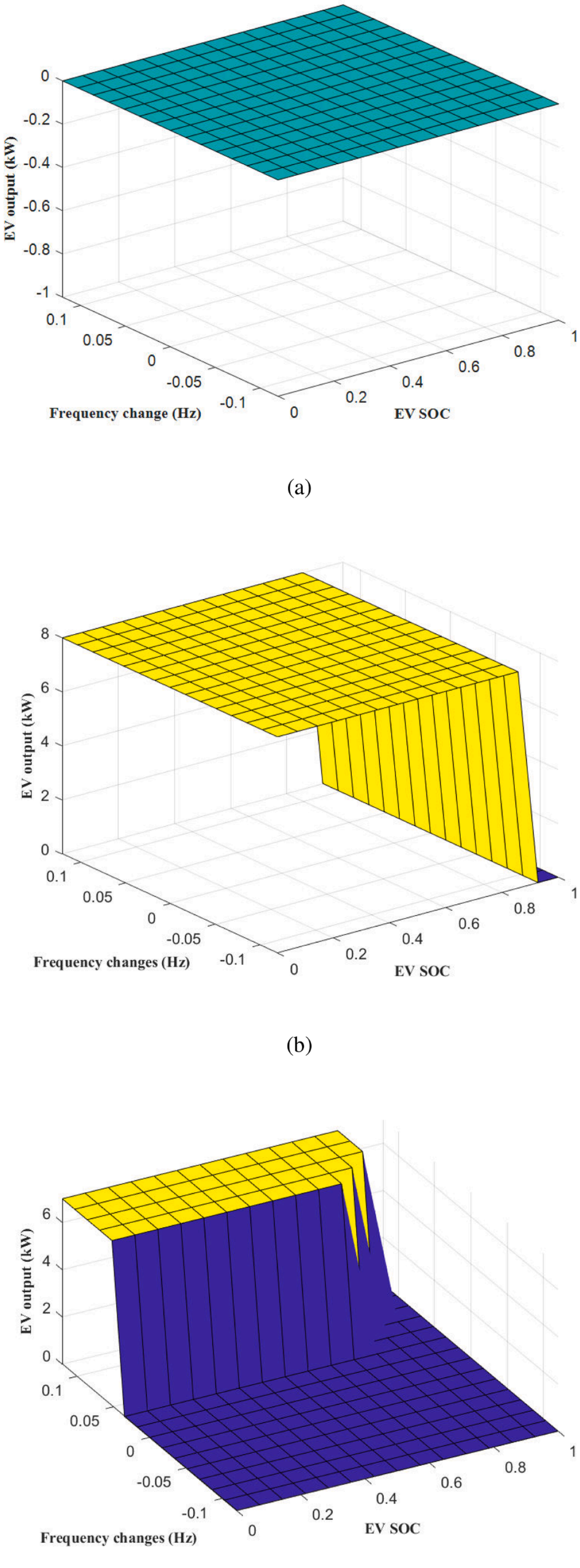
Fig. 6 illustrates how the BESS inverter's active power output reacts regarding the flexibility signals and the SOC. The figure shows that inverter's active power follows a descending trend when the SOC changes from 0 to 1. This means that that the BESS is mainly charged with positive active power when the SOC is low. Correspondingly, it is mainly discharged with a negative value of active power when the SOC is high.

Fig. 6 (a) indicates an ascending trend when the DSO flexibility changes from UB to DB. The active power has a value around zero in cases where the DSO signals are N, SD, and SU. However, it reacts strongly when the DSO requests higher flexibility. When the DSO needs UB, a range between -2.5 to -1.5, it discharges the BESS (negative active power) and when the DSO requires DB, from 1.5 to 2.5, the BESS is charged (positive active power).

As Fig. 6 (b) states, the active-power response to the frequency changes is considerable. The BESS active power equals positive values (charging mode) when the frequency changes are positive and when the TSO needs downward flexibility. Otherwise, the BESS is discharged with negative values when frequency changes are negative and the system requires upward flexibility. The figure also explains that although the BESS reacts to the operators' flexibility needs, it is neither discharged when the SOC is low nor charged when the SOC is high.

Fig. 7 plots the BESS inverter's reactive power in response to the DSO's flexibility needs. As stated before, the inverter's reactive power only reacts to the DSO flexibility needs. The figure indicates that the designed FLC can completely control reactive power based on the DSO's flexibility needs. It consumes reactive power (positive values) in cases where the DSO requests downward flexibility (positive signals). It injects reactive power when the DSO's signals are negative, meaning that the DSO asks for upward flexibility.

Fig. 8 demonstrates the BESS active power changes in the price-based models. The BESS's active power is depicted in terms of the BESS SOC



(a)

(b)

(c)

Fig. 13. EV charging power in response to frequency changes when the DSO needs (a) upward flexibility, (b) downward flexibility, (c) no flexibility.

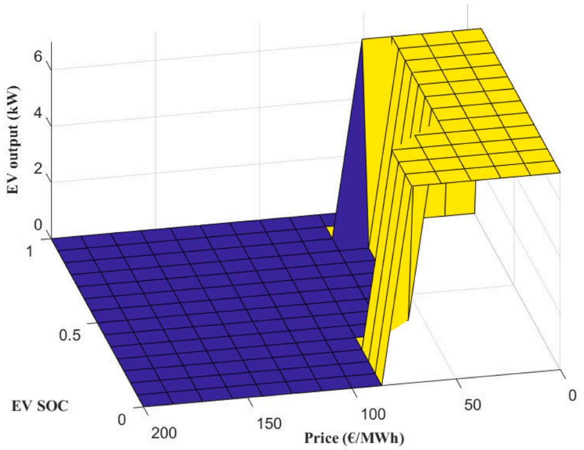


Fig. 14. EV charging power in response to the price signals.

and the price signal. The descending trend of the active power in terms of price states that the BESS is charged in low and medium prices and discharged in high prices. However, the SOC affects the BESS operation as well. The BESS active power only accepts negative values (discharging mode) when the SOC is high and it is positive (charging mode) when the SOC is low. This means that the FLC controls the BESS correctly according to the designed rules.

In the self-sufficient operation, however, the main idea is to use the BESS at its maximum level to increase self-sufficiency. Fig. 9 (a) shows the BESS output curve when the EV SOC is low and the temperature is medium. It demonstrates that the BESS starts being discharged as soon as it reaches the medium BESS SOC level, meaning that it is discharged when the BESS SOC is medium or high. Fig. 9 (b) indicates that the BESS is discharged in most situations. It stops being discharged when the EV SOC is high and the temperature passes the low level. It means that the BESS is only charged when the appliances do not need electricity.

4.1.2. Air-conditioner operation

Fig. 10 represents how the air-conditioner (AC) responds to frequency changes while the DSO requires different flexibility needs. The AC does not react to the frequency changes in Fig. 10 (a) and (b) as long as the DSO needs flexibility. In Fig. 10 (a), the DSO requests upward flexibility from the household and thus the AC output equals zero in medium and high indoor temperatures. In contrast, Fig. 10 (b) demonstrates a situation where the DSO needs downward flexibility. Hence, the AC provides downward flexibility until the temperature reaches its high values.

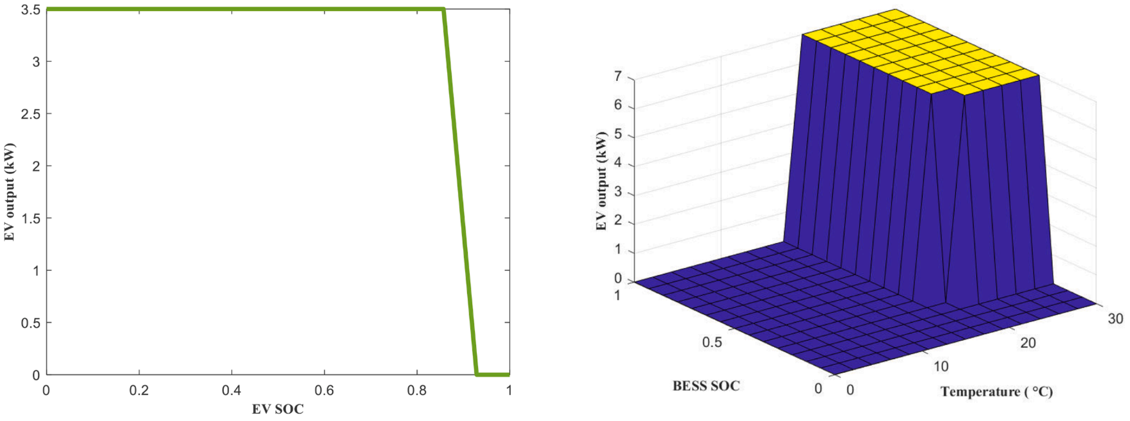
In Fig. 10 (c), the DSO does not ask for flexibility. Therefore, the AC provides upward and downward flexibility according to the frequency changes in the cases where the indoor temperature is in the medium level.

Fig. 11 presents a 3-D plot that models the AC output based on the indoor temperature and price (price-based model). Again, the AC is ON when the temperature is low and it is OFF when the temperature is high. Meanwhile, the flexible shape of the AC output can be seen when the temperature is medium. In this regard, the controller turns the AC on when the price is low and switches it off when the price is high.

Fig. 12 proves the fact that in the self-sufficient model, the AC works only according to the indoor temperature. It means that other inputs such as the EV SOC and BESS SOC cannot affect the operation of the AC in this model.

4.1.3. EV operation

Fig. 13 demonstrates that similar to the AC, EV charging output is more flexible in terms of DSO signals rather than frequency changes. In this regard, when the DSO needs either upward or downward flexibility,



(a) (b)

Fig. 15. EV charging power in the self-sufficient model in terms of (a) EV SOC and (b) BESS SOC and temperature.

Table 5
The parameters related to the household devices that are considered in this paper.

AC-related Parameters				
$P^{AC,max}$ [kW]	α	β[°C /kWh]	θ^{min} [°C]	θ^{max} [°C]
2	0.045	13	18	26
EV-related Parameters				
$P^{EV,max}$ [kW]	Cap^{EV} [kWh]	Charging availability [hour]		η^{EV}
8	40	(0-7) and (18-23) weekdays (0-10) weekends		0.9
BESS-related Parameters				
$P^{ch/dis,max}$ [kW]/ Q^{max} [KVAR]	*Operating Cost* [cent/kWh]		Cap^{BESS} [kWh]	
6	0.7		14	

the EV does not respond to the frequency changes. However, it provides frequency control services in situations where the DSO does not ask for flexibility.

On the other hand, Fig. 14 shows the plot of EV charging output in the price-based models. According to the rules applied to the system, the EV is not charged when the price is high or it has a high SOC level.

Nevertheless, EV charging output is more complex in the self-sufficient model. If the effects of other inputs are disregarded, the EV is charged until its SOC reaches a high level, as Fig. 15 (a) depicts. The BESS SOC and the indoor temperatures, however, have effects on the EV charging schedule. Fig. 15 (b) explains that the EV is charged only when the temperature and BESS SOC are not low. In cases where the BESS SOC is low, the BESS should be charged and it decreases the self-sufficiency if the EV is simultaneously charged. In addition, if the temperature is low, the AC is ON and the BESS should supply the AC output. Thus, it would be more self-sufficient if the EV is not charged when the temperature is low and the AC is turned on.

4.2. Economics analysis

4.2.1. Case study

The economic analyses are conducted on the household considering different operation models. We consider that the household flexible appliances are scheduled for three months from the 1st of January 2021 to the 31st of March 2021. Each flexible device is modeled linearly. The AC is linearly modelled using (5)-(7), in which the ambient temperature and the temperature of the previous time play important roles. The temperatures at the City of Vaasa, Finland, extracted from [38], are

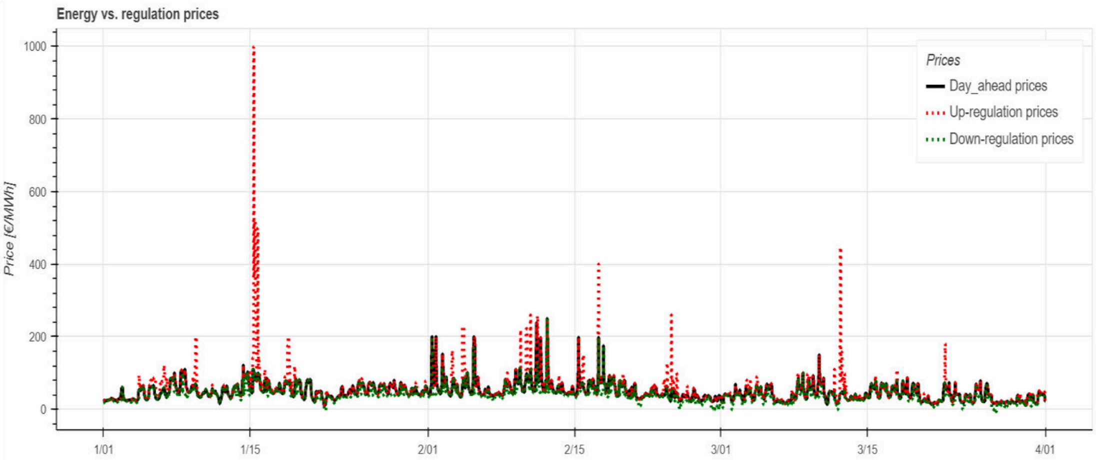


Fig. 16. Comparison of energy market prices with regulation prices for Jan-Apr 2021, Finland.

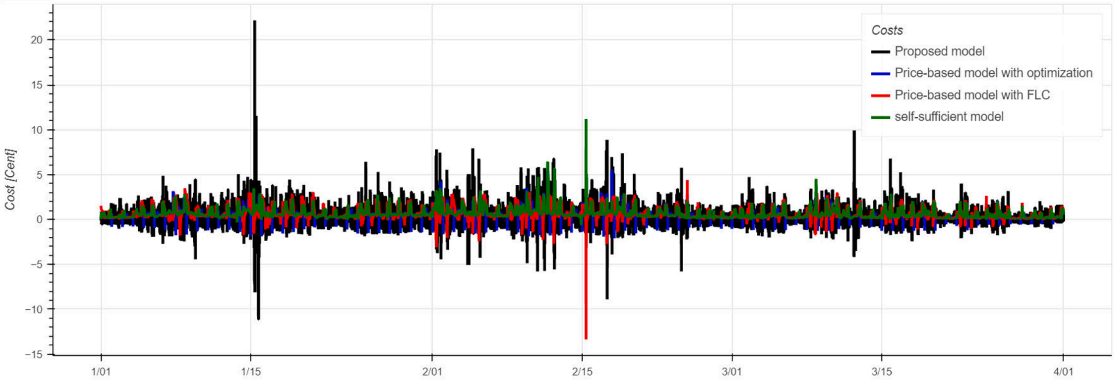


Fig. 17. Costs or incomes obtained from consuming and injecting power in a three-month period considering different models.

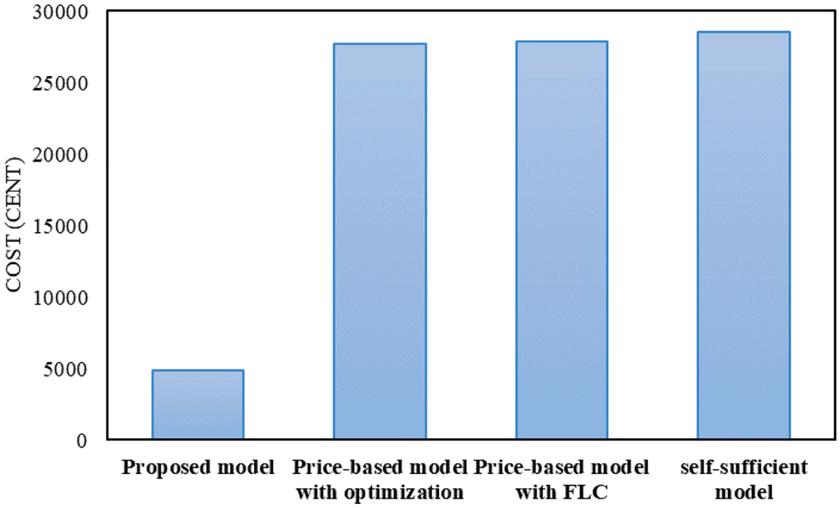


Fig. 18. Total three-month costs obtained from different models according to the day-ahead energy market and regulation prices.

Table 6
Total three-month costs and incomes of the household considering capacity incomes.

Model / Cost [Cent]	Proposed	Price-based with FLC	Price-based with optimization	self-sufficient
Energy and regulation cost	4899.19	27906.32	27735.21	28561.68
Capacity income	≈-21600	-	-	-
Total cost	-16700.81	27906.32	27735.21	28561.68

regarded as the ambient temperatures. Besides, (8)-(10) model the EV SOC in terms of its charging power. The BESS model is developed using (11)-(14). Table 5 shows the appliances' parameters utilized in the modeling process. The household is scheduled every three minutes. Thus, Δt is equal to 0.05.

In the proposed model, the household reacts every three minutes to the frequency changes and provides FCR-N service. The frequency real-time data is obtained from Fingrid open data for Jan-Apr 2021 [41]. Fingrid is the Finnish TSO who is responsible for frequency control in Finland. The household contributing to flexibility provision receives two sources of income: (1) First one is based on the flexible capacities that are reserved for providing flexibility and (2) Second is the payment household receives from provided upward flexibility. The household should pay for the energy consumed when it provides downward flexibility. The prices of upward flexibility are always equal to or higher than those of the day-ahead spot-/energy market whereas the prices of down-regulation are always equal to or lower than those of the day-ahead spot-/energy market. In addition, the household participating only in the day-ahead energy market (spot-market) receives one source of income which depends on how much energy it produces through its BESS discharging. Fig. 16 compares the prices of upward and downward regulations with those of the energy market for Jan-Apr 2021. In respect to Fingrid reserve resource, there are 1.25 cents if there is a reserve of 1 kW of its capacity for FCR-N provisions in 2021 [40]. In this section 5.2, we do not consider the flexibility needs of the DSO. At the moment, there does not exist price data reflecting the DSO-level flexibility. Thus, economic analyses have been conducted for households with only frequency control support related services.

In the price-based model, the household only reacts to energy market spot-prices. Day-ahead prices for the Finland region are adopted from [42] for Jan-Apr 2021.

4.2.2. Simulation results

Finally, a three-month economic analysis is conducted to show whether the proposed model is profitable. In this regard, the price-based and the self-sufficient models trade electricity based on day-ahead energy market prices whereas the proposed model, pays and receives payment based on downward and upward regulation prices. Fig. 17 depicts the costs and incomes that the household receives when it follows different scheduling models. The costs are denoted by positive values while incomes are indicated with negative numbers. Fig. 18 sums all costs and incomes within the three-month period and demonstrates the results by bar plots. Although the costs/incomes of the proposed model are more volatile and uncertain, they lead to a lower total cost. Fig. 18 indicates that the cost of the proposed model is approximately one-fifth of the other models. This is mainly because the proposed model consumes electricity at cheaper prices and sells electricity at more expensive prices. The price-based model with optimization solves the optimization on a daily basis. It sees a longer horizon in the optimization process. Thus, it is more economical compared to the price-based model that uses FLC on a real-time basis. Finally, the self-sufficient model that disregards prices is the less profitable model and incurs higher costs.

As stated previously, the household receives capacity incomes, in addition to regulation costs/incomes if it provides reserve services for the TSO. Regarding the three-month study, the smart home would receive 21600 cents. The capacity payment compensates for the other electricity costs and leads to the household making profits. However, the price-based and self-sufficient models do not receive the capacity payment by participating in the day-ahead energy market. Their total costs are positive values while the proposed model's total cost is equal to a negative value. Table 6 denotes the total costs/incomes of the models that are assessed in this paper.

5. Conclusion and future works

The future renewable-based power systems need more sources of flexibility. Households can be a flexibility provider and help DSOs and TSOs with operating their networks. In this regard, this paper proposed the integration of a fuzzy logic controller into the home energy management system. The aim is to respond to the TSO's needs by reacting to the frequency changes and to provide the DSO with the required flexibility. The paper introduced a cooperative method that prioritizes the local DSO. The proposed inverter-interfaced BESS is able to provide both active power and reactive power flexibility, although the reactive power flexibility is adopted to provide only the DSO with the flexibility.

Finally, the proposed fuzzy logic controller was implemented with enhanced performance. Three other models were also developed to be compared with the proposed model. Two of these models are price-based models in which the household reacts to the day-ahead electricity prices rather than flexibility signals. The other model is the self-sufficient model in which the household disregards the prices and flexibility signals while it tries to be self-sufficient by using its BESS as much as possible for supplying the appliances. The output of each device was analyzed and discussed for different operation models. In addition, a three-month economic analysis was conducted for the household that was scheduled based on different models. The results demonstrate that the total three-month cost of the proposed model was approximately one-fifth of that of the other three models. In addition to that, the proposed model received a considerable capacity payment (around € 216) that compensated the household costs and brought profits for the household.

Finally, this work can be expanded in the future in the following directions:

1- The proposed FLC-based management system can be developed and analyzed for a community of smart homes with smart controllable appliances and the community's shared assets. In this way, the energy community would be able to provide a considerable amount of flexibility services for system operators.

2- The FLC-based management system can be developed to control industrial devices. In this way, industrial loads would be able to provide coordinated services for both TSOs and DSOs.

3- It is very simple to retrofit the proposed fuzzy logic-based methodology on any power electronics interfaced with embedded programing and to serve utilities as services owned by prosumers with further communications on the distribution system.

CRediT authorship contribution statement

Hosna Khajeh: Conceptualization, Methodology, Investigation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Hannu Laaksonen:** Supervision, Validation, Writing – original draft, Writing – review & editing. **Marcelo G. Simões:** Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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