

# A Systems Theory Approach for Complex Energy Systems: A Case Study of Peer-to-Peer Energy Sharing

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**Abstract:** Due to the complexity of energy systems, they require robust control methods to ensure efficient operation. This is particularly true when reconfiguration is required to increase the system's resilience. One such scenario is when Peer-to-Peer (P2P) energy trading is employed. This work uses systems theory to model and optimize complicated systems when several assets with heterogeneous characteristics are interconnected. This is achieved by adopting graph theory, propositional logic and state space analysis of dynamical systems. This approach simplifies P2P energy exchange and improves the system's efficiency and resilience. The results obtained showed that the complexity of modelling P2P systems using structures like flowcharts increases with addition or introduction of new peers to the network and/or constraints on the network's Energy Management System (EMS). The results obtained were validated by comparing the outcome of a P2P system modelled using E-variables and that modelled using structures like flowchart. We proved that using the proposed approach, it is easy to model such complicated systems. Since it is scalable, it can easily accommodate changes in the EMS (which manages how subsystems within a microgrid operate in order to ensure system efficiency) without significantly modifying the representation of the EMS.

**Keywords:** Distributed energy resources; E-variables; Energy management strategy; Microgrid; Peer-to-peer.

## 1. INTRODUCTION

The rapid exhaustion of fossil-based fuels reserves is continually leading to their global scarceness. Driven by this scarcity and other environmental issues like pollution and global warming, the use of Renewable Energy Sources (RES) is proliferating [1-3]. RES, for example solar and wind energy sources are environmentally friendly [4] and are consumed at an insignificant rate when compared to their supply. One of the biggest challenges of RES, however, is their reliance on climate conditions and variable resources [4-7]. This dependency makes their energy output stochastic and unreliable to continuously satisfy demand requirements [8]. For this reason, an energy storage system is an important asset in balancing the energy supply and demand. Conventionally, the electric grid is a one-way flow of energy from the utility to the consumers. However, the recent proliferation of distributed energy resources (DER) has dramatically transformed how energy is generated, transmitted and consumed in the electric grid. Recent technological advancements made possible the integration of DER to the grid, consequently transforming some traditional consumers into prosumers. A prosumer not only consumes but is also driven to generate energy locally by economic and environmental concerns [9]. Policies like the net metering and feed-in-tariff by utility companies also contributed to these transformations [10]. The utilities implemented these policies to modify consumer load demands to be more flexible or to bring energy consumption under control [11, 12].

Nevertheless, the stochastic nature of DERs and variable consumer load demand introduced complex control challenges to the grid [13]. Therefore, there is a need to make decisions with regards to the deployment of DER at the appropriate instances in order to address the varying temporal behavior they inflict in a system [1]. Scientists are continually redefining some fundamental aspects of DER regarding their policies, framework, management, planning, optimization, and operation with the main aim of improving overall efficiency and reducing energy cost [14]. A micro-grid (MG) is considered a great solution for addressing the grid control problems. It is a self-supporting decentralized energy system that operates synchronously to the grid either autonomously or connected to it. A microgrid ensures effective utilization of DER [15, 16]. However, the stochastic characteristics of RES bring about a supply-demand mismatch. One solution for this problem is using distributed energy storage devices to get rid of energy surplus or deficiency, but it is not promising. This failure is because storage devices are associated with losses in the process of charging and discharging them and huge investment expenses [16, 17].

Peer-to-Peer (P2P) energy sharing is another solution for the grid control problem. It is an intriguing approach in multi-vector energy systems [16, 18] and can offer great advantages. These advantages include reduced DER curtailment, increased efficiency, tackling energy supply-demand mismatch locally, improved power system reliability and optimal exploitation of

DER. However, when multiple users are involved, and particularly when reconfiguration is required (for example to increase the system's resilience) the complexity of the overall system and control methodology is greatly increased.

Decisions regarding the interaction between sub-systems within or between MGs are usually addressed in a hierarchy. The decisions taken at a higher level involve energy sharing among distinct micro-grids. The lower level comprises control approaches applied to a specific sub-system, while the middle level encompasses the local decisions within a MG [15]. This work will cover the decision at the middle levels (using system theory approach). Satisfying local loads in a P2P entail determining the efficient modes of interoperation among integrated sub-systems in a MG. To plan an overall efficient control scheme, the system's responses are studied under time scales [15]. This kind of study is known as Energy Management Strategy (EMS) and is usually decisions regarding the appropriate instant to activate or deactivate a sub-system, the duration of their operation and the constraints under which they should be operated. EMS is either obtained from the mathematical optimization process or is a specific set of predetermined options.

The optimization of renewable power systems can be achieved by extracting maximum power, sizing or energy management which is more relevant to grid-connected systems [19]. Several works of literature [15, 20, 21] suggested implementation of EMS using simple rules expressed as "if-else statements" or using structures like flowchart diagrams. Most of the existing studies rely on a flowchart in representing EMS for complex power systems including P2P energy trading schemes. However, this kind of approach has limitations because its complexity increases as the number of peers, devices and conditions imposed on devices interoperation in the P2P scheme increase.

The authors in [22] proposed a P2P energy trading in a smart home between two prosumers and consumers with the main objective of minimizing their cost of electricity. The proposed model was implemented using demand response based on real-time pricing. First, smart appliances in each home are scheduled based on real-time pricing (RTP) using a binary particle optimization algorithm. Then, P2P is implemented amongst prosumers and consumers based on demand response implementation. The EMS of the proposed P2P energy trading scheme is formulated using a flowchart. However, this energy management representation approach is not practical due to additional complexity introduced to the flowchart from additional peers.

A P2P scheme between a building (equipped with photovoltaic (PV) generation) and a group of electric vehicles within a charging station is proposed to improve the benefit of all the parties through the EMS [23]. Though, only an overview of the EMS was presented, using a flowchart, due to its complexity. Similarly in [24], the authors proposed a multi-objective predictive control EMS for a grid-connected residential hybrid energy system based on a machine learning technique for residential buildings. The control method is implemented in a hierarchy. For accuracy management and computational load, logical control of data flow was proposed. For predictions of future load demand and energy production, a machine learning model was used. Lastly, for battery charge scheduling, a multi-objective optimization was formulated considering the machine learning predictions, CO<sub>2</sub> emissions, cost of electricity and state of charge of the battery system as objectives for each time step. A flowchart was used in representing the proposed EMS for the single residential building. Nevertheless, this method will break down if new devices or constraints will be added to the EMS. Likewise, an energy management algorithm to optimize the operational energy losses of residential households through control of their energy sources (grid, solar and battery) was proposed [19]. The EMS (represented using flowchart) schedule consumption giving priority to solar production, followed by the battery and the grid. In the same way, [25-28] proposed a P2P energy trading scheme in which the EMS was represented using a flowchart. Nevertheless, only a summary of EMS was captured by the flowchart due to its complexity. Thus, it is essential to have a flexible method of representing EMS that can provide a flexible avenue to model complex power systems. In [15], the authors proposed implementation of an EMS using a novel method referred to as evolution e-variables. In this paper, we demonstrated that this approach could be used in a P2P case study, where particular attention is drawn on reconfiguring the network or the EMS. To this end, we proposed modelling EMS of power systems undertaking P2P energy sharing using e-variables.

The main contributions of this work are summarized as follows:

- The main aim of this study is to propose a systematic method of representing EMS capable of providing a more flexible avenue to model energy systems undergoing P2P energy sharing with many peers, devices, and constraints.
- Modelling P2P energy trading between two prosumers, each having energy source (grid and PV-arrays), energy storage system (battery) and load, using e-variables in which EMS is represented using a combination of logical and relational operators to impose constraints and express decisions.
- Demonstrated the scalability of the proposed method of representing EMS by modelling a P2P energy trading between any number of prosumers.
- Demonstrated how imposing/introducing new constraints in the system's EMS will not make the EMS representation intricate.

The rest of the paper is organized as follows. Section two describes the input profiles and general configuration of the proposed system, including PV array, load, grid, battery, and converters. Section 3 presents the general model (e-variable) of the proposed system, including the energy management representation used in this work. The EMS of a P2P energy sharing scheme is modelled using a flowchart and then e-variables in Section 4. Finally, the conclusion is presented in Section 5.

## 2. GENERAL SYSTEM STRUCTURE AND INPUT PROFILES

Figure 1 shows a general architecture of the systems which will be considered in this work. It consists of PV arrays connected to a direct current (DC) Bus via a DC-DC converter. Additionally, there is a battery which connects to the DC Bus in two-way manner. Using a bidirectional converter, the DC Bus is connected to an alternating current (AC) Bus. The loads at the consumer premises and the grid are all connected via the AC Bus.

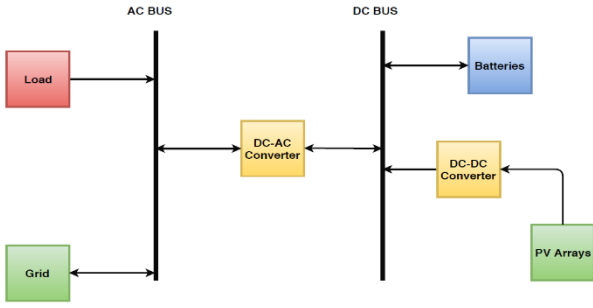


Figure 1. Block diagram of the systems general architecture

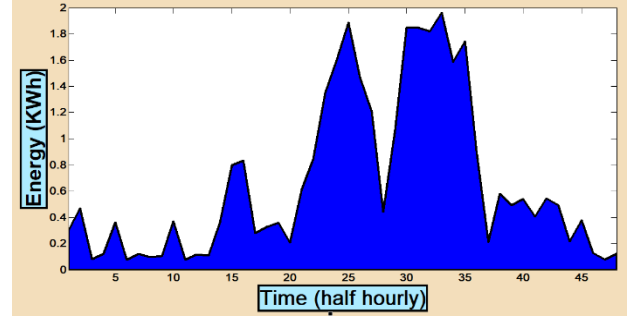


Figure 2. Daily load profile of typical UK residence

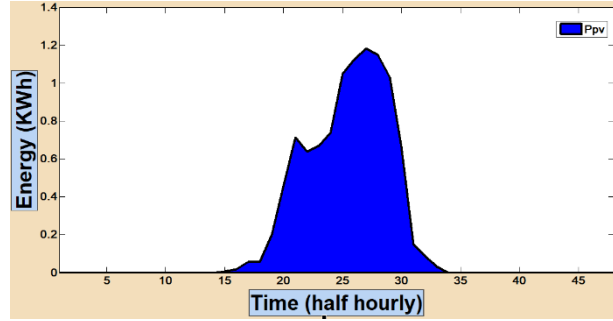


Figure 3. Daily PV generation profile

The data used as the load profile is the load profile of a typical UK home (residence). The daily load profile of a typical UK residence plotted over time (half hourly) is shown in Figure 2. There are two peak demands over the whole period both having a value just below 2 kWh. These maximum demands depend on the daily consumption pattern of the consumer. There are also periods where the demand is low, and these are mainly occurring during night hours. They also occur during the daytime when a consumer is not using his appliances. The PV profile used also is the data of a typical UK household. Figure 3 shows the PV generation profile plotted over time for a single day. The PV generation usually depends on the sun radiation. Figure 3 clearly shows that the generation is zero at night hours where the solar radiation is negligible. The generation increased as the sun radiation increases, reaching its peak value of approximately 1.2 kWh at midday.

The load and PV profiles used for the P2P system which requires more than one PV and load profiles are derived from the original profiles presented above. System (A) will always use the original data as it is, while for system (B), the load profile was taken to be one and a half times that of systems (A). Similarly, the PV profile for system (B) was taken as ten (10) times bigger than that of system (A). This approach is necessary because no two-consumer premises will have the same consumption pattern as they will have different devices of different ratings. Each of the systems (both A and B) will have a specific EMS which controls power flow among devices within it. The EMS will be modelled using either flowchart or e-variables and then implemented as codes on MATLAB. E-variables is a method proposed in [15] to represent EMS used in complicated energy systems, and it uses a combination of logical/relational operators to express the EMS and impose constraints.

### 3. EVOLUTION VARIABLES (E-VARIABLES)

#### 3.1 Systems General Network Model

It is necessary to model the system in a generic way before developing a representation of its energy management decisions. The model must be able to capture all energy flows among interconnected subsystems irrespective of their roles. Firstly, the system is considered as a network and each of its interconnected subsystems as nodes. The line connecting devices together (i.e. energy line) will be denoted as edges. In the system presented, devices can have multiple inputs and outputs flows in form of power. All the system's incorporated devices are classified into either converters or storage devices. A converter is a device that transform energy from one state to another while a storage device is any device that stores energy like battery in our case. The load and the PV arrays form the set of converters in the given system. The loads are considered as a converter but one without any output flow.

Based on the information above the energy flow among devices in the system at instant  $k$  is given by:

$$F_n^{in}P(k) = SF_nP(k) + \sum_l (\varepsilon_{l-n}(k) * F_{l-n}^{out}(k)) + \sum_k (\varepsilon_{m-n}(k) * F_{m-n}^{out}(k)) \quad (1)$$

where  $k$ ,  $SF_nP(k)$ ,  $F_{l-n}^{out}(k)$  and  $\varepsilon_{m-n}(k)$  represent the time, power, probable external input (like solar radiation), output of node  $l$  going to node  $n$  at the instant  $k$  and binary variable that determines connection of specific edge, respectively. If there is a physical connection between node  $m$  and node  $n$  then the variable is one (1) and zero (0) otherwise. Activation of certain

connection depends on some conditions that when true, the connection will be active and if false will be inactive. It should be noted that a flow from a node  $m$  may split to different devices according to Equation (2):

$$F_n^{out} P(k) = a_{m-n}(k) \times F_n^{out} P(k) \quad (2)$$

where  $F_n^{out}(k)$  is output vector of node  $n$ ,  $P(k)$  is power at instant  $k$  and  $a_{m-n}(k)$  is part of the output of node  $m$  that goes to node  $n$  in form of power  $\sum_m a_{m-n}(k) = 1$ .

For storage device the state of charge of the battery is given by Equation (3),

$$SOC_{Bat}(k+1) = SOC_{Bat}(k) + \frac{F_{m-n}^{in}(k) - F_{n-m}^{out}(k)}{C_n} \quad (3)$$

where  $SOC_{Bat}(k+1)$  is the amount of stored energy in a storage device at the next instant,  $SOC_{Bat}(k)$  is the amount of stored energy in the SD at the instant  $k$ ,  $C_n$  is the capacity of storage device,  $F_{m-n}^{in}(k)$  is output of node  $m$  going to node  $n$  at the instant  $k$  and  $F_{n-m}^{out}(k)$  is output of node  $n$  going to node  $m$  at the instant  $k$ .

### 3.2 Energy Management Representation

The definition e-variables will be given in a flexible and systematic way. The activation and deactivation of a connection between two connected nodes depends on three conditions as follows:

- The availability of energy of device  $m$ , and it is given by  $\varepsilon_{m-n}^{avl}(k)$ .
- The requirement for energy of devices  $m$ , and  $n$  considering  $m \neq n$ , is given by  $\varepsilon_{m-n}^{req}(k)$ .
- Other desirable specific conditions that are not associated with the above two is given by  $\varepsilon_{m-n}^{Gen}(k)$ .

The e-variable can be further defined as:

$$\varepsilon_{m-n}(k) = L(\varepsilon_{m-n}^{avl}(k), \varepsilon_{m-n}^{req}(k), \varepsilon_{m-n}^{Gen}(k)) \quad (4)$$

where  $L$  is logical operator that is determined by the EMS and  $\varepsilon_{m-n}(k)$  is binary variable that determine connection of specific edge. The variables  $\varepsilon_{m-n}^{req}(k)$  and  $\varepsilon_{m-n}^{avl}(k)$  are used to express conditions imposed by the EMS,

$$\varepsilon_{m-n}^{avl}(k) = L_{m-n}^{avl}(P_{m-n}^{SOCsd1}(k)) \quad (5)$$

$$\varepsilon_{m-n}^{req}(k) = L_{m-n}^{req}(P_{m-n}^{SOCsd2}(k)) \quad (6)$$

where  $P_{m-n}^{SOCsd}(k)$  a binary variable that becomes 1 when a condition(s) is satisfied and zero otherwise. The condition depends on the energy stored in the storage device. It accounts for ON-OFF switching of the devices.

## 4. RESULTS AND DISCUSSION

### 4.1 Peer-to-Peer Energy Sharing

The P2P scheme enables local energy trading between prosumer (A prosumer not only consumes electricity but is also motivated to generate locally by several factors) in a given community. As an initial case study, there are two system/premises considered here, i.e. premises A and premises B. Each system has a PV-battery system consisting of a PV-panel, a battery, and a local load. Figure 4 shows a block diagram modelling power flows for the system if P2P energy sharing is enabled. There are twelve interconnections between devices and subsystems representing power flow. It should be noted that the net power is the difference between the power generated in a premises and the local load consumed i.e. ( $P_{net} = P_{pv} - P_{ld}$ ). There are four possible scenarios for the system considering the net power. These scenarios are:

- $P_{netA} > 0$  and  $P_{netB} > 0$
- $P_{netA} < 0$  and  $P_{netB} < 0$
- $P_{netA} > 0$  and  $P_{netB} < 0$
- $P_{netA} < 0$  and  $P_{netB} > 0$

P2P exchange requires at least two systems in which one is generating excess power and the other is deficient as in the last two scenarios, (c) and (d). The state of charge of the battery must be considered also for P2P energy exchange. For example, the conditions to be fulfilled for energy exchange from  $A$  to  $B$  are:  $P_{netA} > 0$ ,  $P_{netB} < 0$ ,  $SOC_{BatA} > 0.8$  and  $SOC_{BatB} < 0.3$ , where  $SOC_{BatA}$  and  $SOC_{BatB}$  represent the state of charge of battery  $A$  and  $B$  respectively. Similar conditions hold the other way round i.e. energy sharing from  $B$  to  $A$ . The only scenario that will logically allow selling power to the grid is scenario (a) that is when both premises produce surplus power and the state of charge of their storage devices are above their recharging threshold. Scenario (b) represents an instant when both systems net power is less than zero and, in this case, they will have to source power from either the grid or the battery. This decision of sourcing power from grid or battery, depends on a system's state of charge of battery. All the above decisions are determined by the system's EMS. The EMS is then modelled using flowchart and then coded on MATLAB utilising "if else statements".

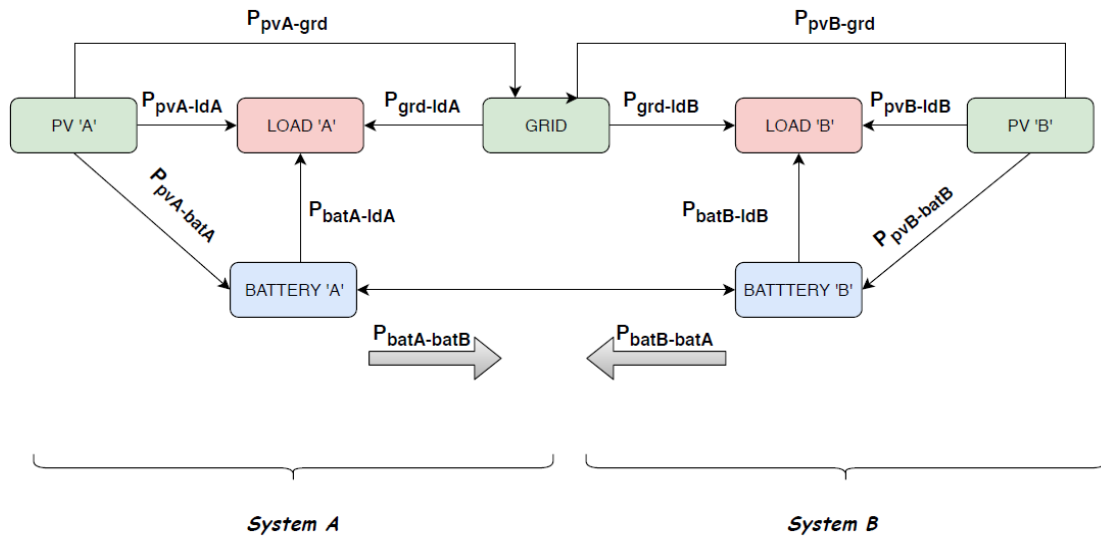


Figure 4. Block diagram model for P2P energy sharing

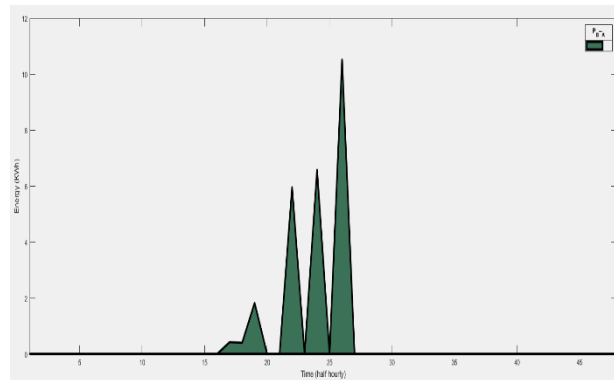


Figure 4. Daily power transferred from System (B) to System (A)

The initial state of charge of battery A and battery B is 0.2 (representing twenty per cent of battery capacity) and 1.0 (representing full battery capacity) respectively. After the MATLAB script was run, an energy flow from system (B) to system (A) was recorded as shown in Figure 5. The figure showed three peak energy transfer from system A to system B of about 10.5 kWh (single) and roughly 7 kWh (double) which happen between 10:00 and 16:30. The minimum energy shared is all below 2 kWh.

The EMS used for this system is modelled in the form of a flow chart and is shown in Figure 6. The flowchart starts with calculating net power in both premises A and B from the input profiles. Then a loop is created that checks the state of charge of the battery in each premises at half hour intervals. The algorithm activates a connection between interconnected devices based on the state of charge of batteries and net power in each premises at particular instance. For simplicity, the flowchart has been compacted onto different sections depending on the net power of the systems. Subprogram 1 and 3 depict scenarios where both systems have net power greater than zero and less than zero respectively. Subprogram 2 and subprogram 4 in Figures 6 and 7 respectively are the parts of the flowchart in which P2P energy exchange is implemented. The complete flowchart of the system is not presented here because of its size. A critical feature about modelling EMSs using structures like flowcharts is that they become more complex as the system scales up in terms of the number of peers and devices in the system.

In order to further illustrate how the complexity is affected with even a simple change in the EMS, a small arbitrary constraint is introduced to the EMS. Currently the battery from each premises charges via the surplus from the PV generation. Now, let one of the premises (say B) decide to charge its battery from the grid during night hours in addition to charging from the PV surplus generation. Night hours are chosen arbitrarily and because it is usually the time when the demand is so low to the extent that the retail price is negative at some instances. This effectively means a consumer will get paid to consume energy and effectively increasing his economic benefit. Upon the reflection of this constraint to the EMS, the system's flowchart changes significantly, and the corresponding modifications are shown in Figures 8, 9 and 10.

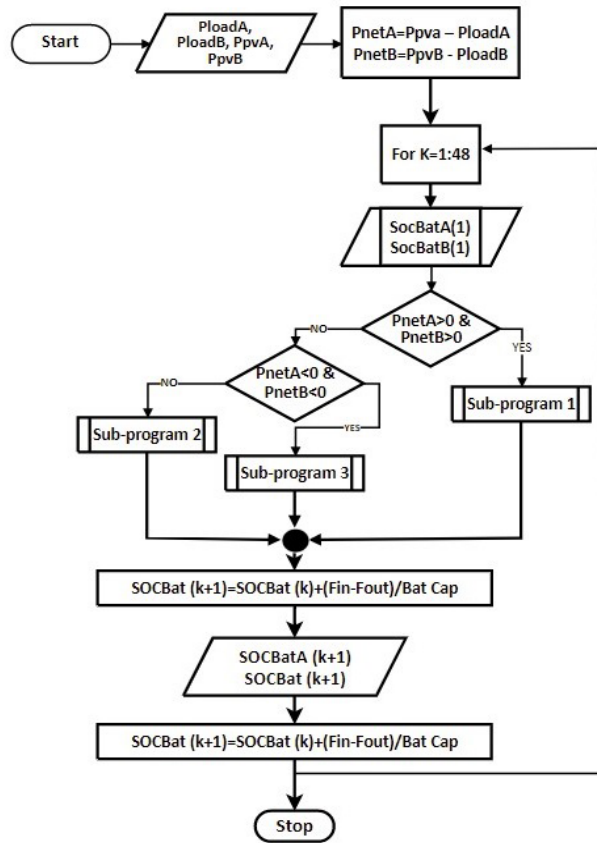


Figure 5. Flowchart representation for P2P energy sharing between two peers

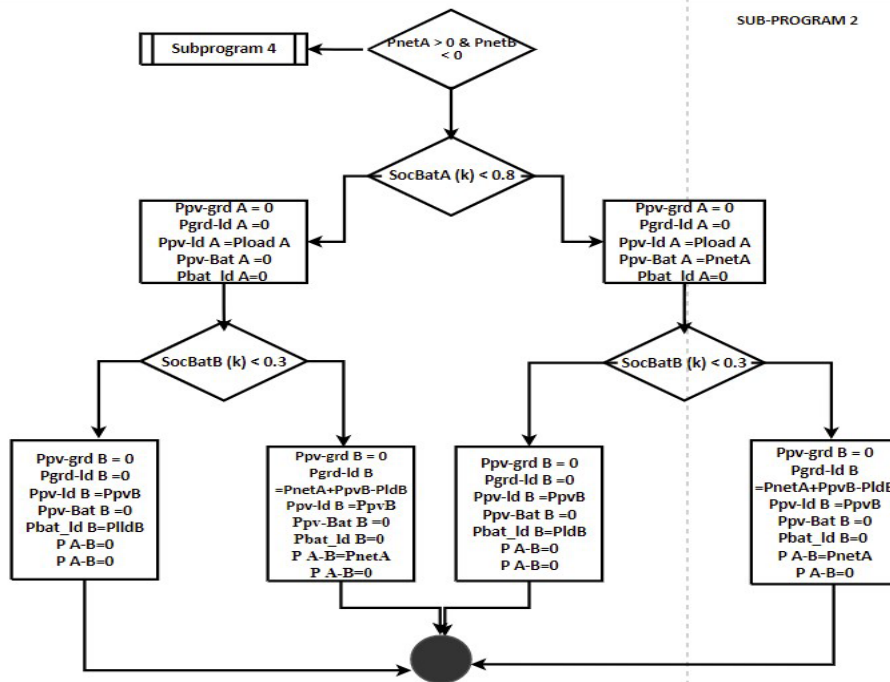


Figure 6. P2P energy sharing sub-program 2 flowchart 1

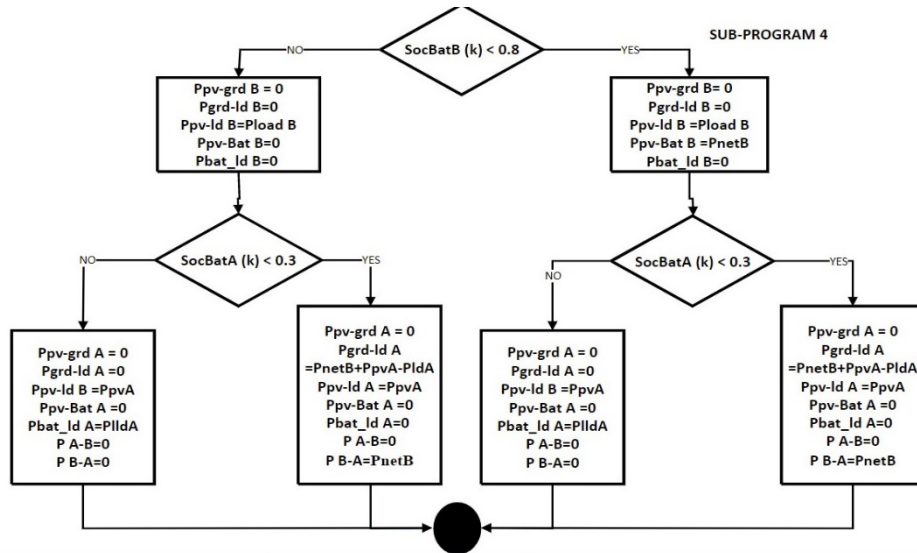


Figure 7. P2P energy sharing sub-program 4 flowchart

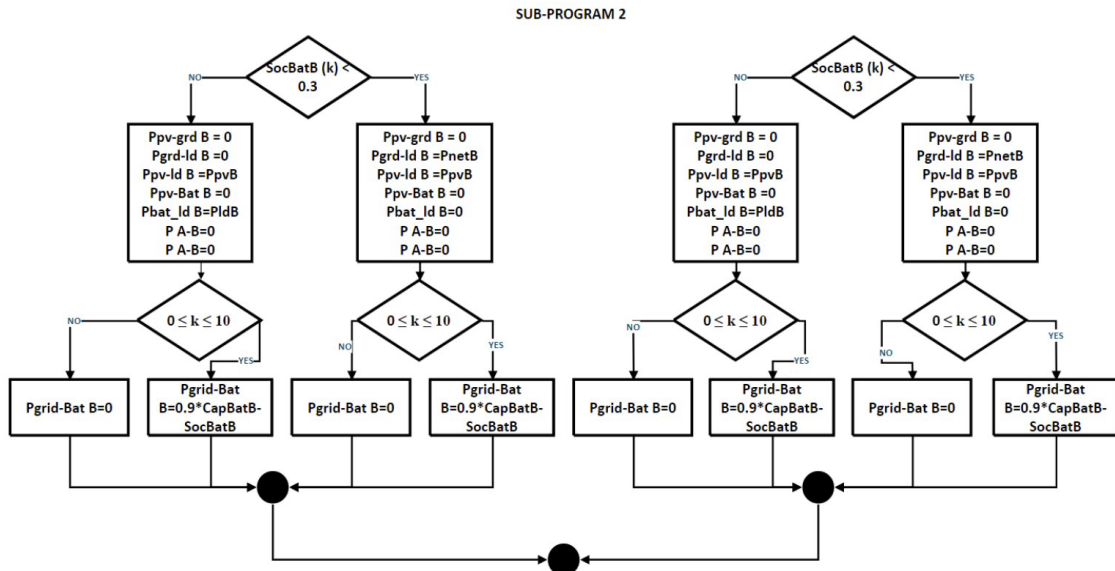


Figure 8. Flowchart of the first section of the additional constraint

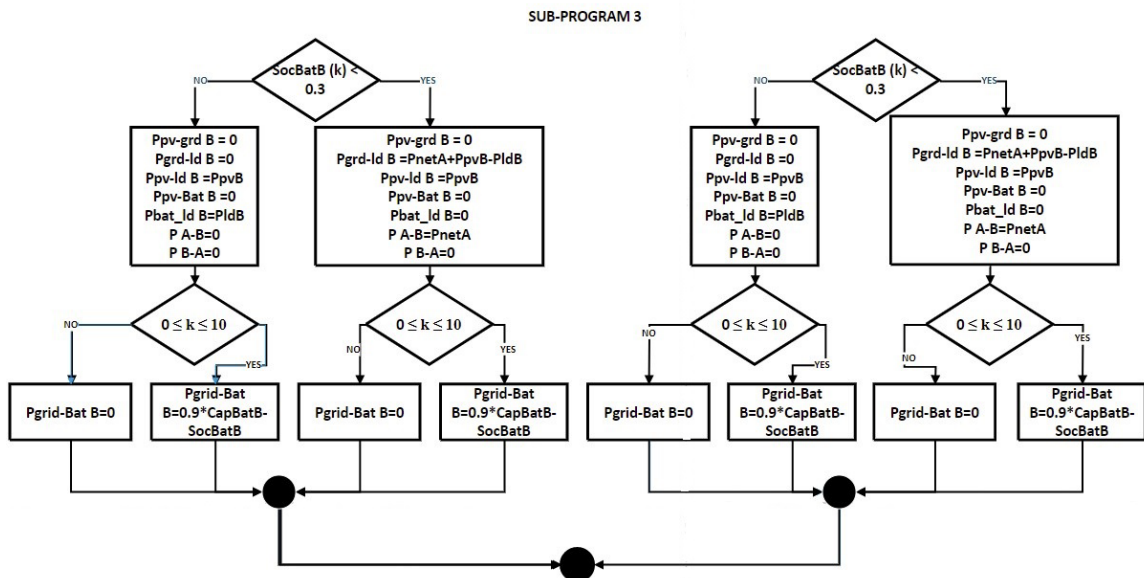


Figure 9. Flowchart of the second section of the additional constraint

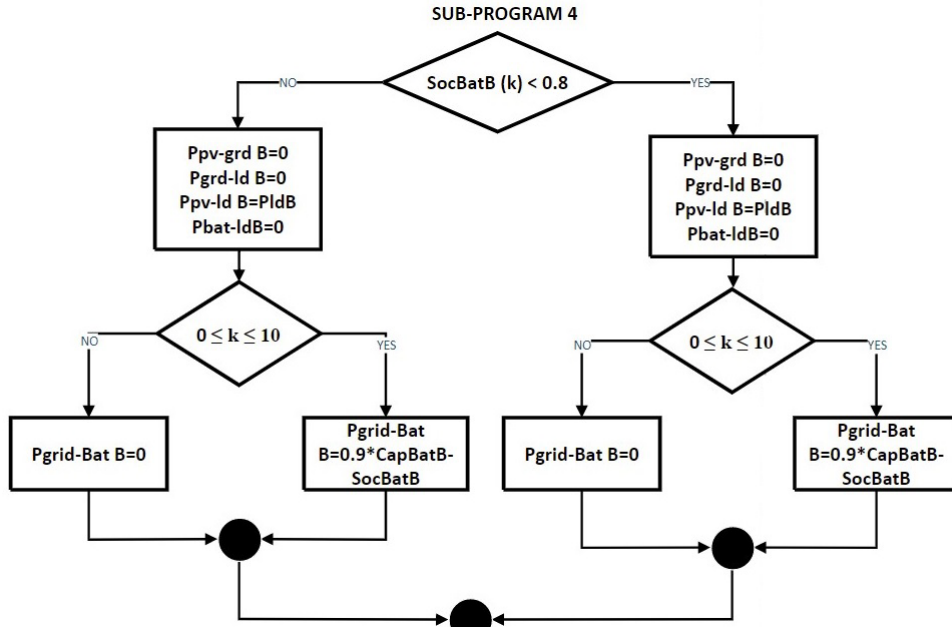


Figure 10. Flowchart of the third section of the additional constraint

The complexity discussed and illustrated above will almost makes it impractical to use flowcharts and “if else statements” to implement a EMS of real-life systems. It is impractical because real systems are by nature complex and it have been illustrated how even a small constraint can give rise to a complex flowchart. Therefore, a new systematic method needs to be used for simple, easy and flexible representation of EMS of P2P systems.

#### 4.2 Modelling P2P Energy Exchange using E-Variables

Consider the system shown in Figure 4, in order to be able to model it using e-variables. First, we define the e-variables for each of the twelve connections within the system.

##### a) $P_{pvA-ldA}$

The first connection is between the local load and the PV in premises A. This connection is activated whenever the availability and requirements conditions are satisfied else otherwise. The availability condition is that the PV produce some amount of energy that is greater than zero at a particular instant  $k$  and is expressed as:

$$\varepsilon_{pvA-ldA}^{avl}(k) = P_{pvA}(k) > 0$$

Now the requirement conditions for this connection are divided into two ( $\varepsilon_{pvA-ldA}^{req}1(k)$  and  $\varepsilon_{pvA-ldA}^{req}2(k)$ ) depending on whether they are mutually exclusive or otherwise. The first requirement is that the net power in both premises A and premises B are simultaneously greater than zero or the net power in premises A is greater than zero and at same moment that of premises B is below zero. The second requirement is that the net power in both premises A and B are simultaneously greater than zero or the net power in premises A is under zero and at same moment that of premises B is greater than zero. Whenever the availability and requirement conditions are true the corresponding connection will be activated thus allowing power flow. These conditions are expressed in notations as:

$$\varepsilon_{pvA-ldA}^{req}1(k) = ((P_{netA}(k) > 0) \wedge (P_{netB}(k) > 0)) \vee ((P_{netA}(k) > 0) \wedge (P_{netB}(k) < 0))$$

$$\varepsilon_{pvA-ldA}1(k) = (\varepsilon_{pvA-ldA}^{avl}(k) \wedge \varepsilon_{pvA-ldA}^{req}1(k))$$

$$\varepsilon_{pvA-ldA}^{req}2(k) = ((P_{netA}(k) > 0) \wedge (P_{netB}(k) > 0)) \vee ((P_{netA}(k) < 0) \wedge (P_{netB}(k) > 0))$$

$$\varepsilon_{pvA-ldA}2(k) = (\varepsilon_{pvA-ldA}^{avl}(k) \wedge \varepsilon_{pvA-ldA}^{req}2(k))$$

##### b) $P_{pvA-grd}$

The second interconnection is between the PV in premises A and the grid. The connection will be activated whenever the availability and requirement conditions are met. The availability condition is that the net power in premises A is greater than zero at a particular instant  $k$ . The requirement condition is that the state of charge of battery in premises A and premises B are above 0.8 and the net power in premises B is also greater than zero all simultaneously. These conditions are expressed as:

$$\varepsilon_{pvA-grd}^{avl}(k) = P_{netA}(k) > 0$$

$$\varepsilon_{pvA-grd}^{req}(k) = (socbatA(k) > 0.8) \wedge (P_{netB}(k) > 0) \wedge (socbatB(k) > 0.8)$$

$$\varepsilon_{pvA-ldA}(k) = \left( \varepsilon_{pvA-grd}^{avl}(k) \wedge \varepsilon_{pvA-grd}^{req}(k) \right)$$

The availability and requirement conditions are used to define e-variables for the other ten interconnections in a similar manner.

c)  $P_{grd-ldA}$

It is assumed that the power from the grid is always available and based on this assumption the availability condition here is neglected.

$$\varepsilon_{grd-ldA}^{req}1(k) = (P_{netA}(k) < 0) \wedge (socbatA(k) < 0.3) \wedge (P_{netB}(k) < 0)$$

$$\varepsilon_{grd-ldA}^{req}2(k) = (P_{netA}(k) < 0) \wedge (socbatA(k) < 0.3) \wedge (P_{netB}(k) > 0) \wedge (socbatB(k) < 0.8)$$

$$\varepsilon_{grd-ldA}1(k) = \varepsilon_{grd-ldA}^{req}1(k)$$

$$\varepsilon_{grd-ldA}2(k) = \varepsilon_{grd-ldA}^{req}2(k)$$

d)  $P_{pvA-batA}$

$$\varepsilon_{pvA-batA}^{avl}(k) = P_{netA}(k) > 0$$

$$\varepsilon_{pvA-batA}^{req}1(k) = (socbatA(k) < 0.8) \wedge (P_{netB}(k) > 0)$$

$$\varepsilon_{pvA-batA}^{req}2(k) = (socbatA(k) < 0.8) \wedge (P_{netB}(k) < 0)$$

$$\varepsilon_{pvA-batA}1(k) = \left( \varepsilon_{pvA-batA}^{avl}(k) \wedge \varepsilon_{pvA-batA}^{req}1(k) \right)$$

$$\varepsilon_{pvA-batA}2(k) = \left( \varepsilon_{pvA-batA}^{avl}(k) \wedge \varepsilon_{pvA-batA}^{req}2(k) \right)$$

e)  $P_{batA-ldA}$

$$\varepsilon_{batA-ldA}^{avl}(k) = socbatA(k) > 0.3$$

$$\varepsilon_{batA-ldA}^{req}1(k) = (P_{netA}(k) < 0) \wedge (P_{netB}(k) < 0)$$

$$\varepsilon_{batA-ldA}^{req}2(k) = (P_{netA}(k) < 0) \wedge (P_{netB}(k) > 0)$$

$$\varepsilon_{batA-ldA}1(k) = \left( \varepsilon_{batA-ldA}^{avl}(k) \wedge \varepsilon_{batA-ldA}^{req}1(k) \right)$$

$$\varepsilon_{batA-ldA}2(k) = \left( \varepsilon_{batA-ldA}^{avl}(k) \wedge \varepsilon_{batA-ldA}^{req}2(k) \right)$$

f)  $P_{batA-batB}$

$$\varepsilon_{batA-batB}^{avl}(k) = socbatA(k) > 0.8$$

$$\varepsilon_{batA-batB}^{req}(k) = (P_{netA}(k) > 0) \wedge (P_{netB}(k) < 0) \wedge (socbatB(k) < 0.3)$$

$$\varepsilon_{batA-batB}(k) = \left( \varepsilon_{batA-batB}^{avl}(k) \wedge \varepsilon_{batA-batB}^{req}(k) \right)$$

g)  $P_{batB-batA}$

$$\varepsilon_{batB-batA}^{avl}(k) = socbatB(k) > 0.8$$

$$\varepsilon_{batB-batA}^{req}(k) = (P_{netA}(k) < 0) \wedge (P_{netB}(k) > 0) \wedge (socbatA(k) < 0.3)$$

$$\varepsilon_{batB-batA}(k) = \left( \varepsilon_{batB-batA}^{avl}(k) \wedge \varepsilon_{batB-batA}^{req}(k) \right)$$

The rest of the definitions for premises “B” are similar to the ones in premises A. The next step is to determine the power flow into individual nodes/devices/assets. Power flowing into a battery is given by:

$$F_{batA}^{in}P(k) = \sum_l^N (\varepsilon_{l-batA}(k) \times F_{l-batA}^{out}P(k)) \quad (7)$$

Therefore, power flowing into battery (A) in premises A is given as:

$$F_{batA}^{in}P(k) = \left( \varepsilon_{pvA-batA}(k) \times P_{netA}(k) \right) + \left( \varepsilon_{batB-batA}(k) \times P_{netB}(k) \right)$$

Power flowing into battery (B) in premises B is expressed as:

$$F_{batB}^{in}P(k) = \left( \varepsilon_{pvB-batB}(k) \times P_{netB}(k) \right) + \left( \varepsilon_{batA-batB}(k) \times P_{netA}(k) \right)$$

Power flowing into the Grid is expressed as:

$$F_{grd}^{in}P(k) = \left( \varepsilon_{pvA-grd}(k) \times P_{netA}(k) \right) + \left( \varepsilon_{pvB-grd}(k) \times P_{netB}(k) \right)$$

Power flowing into load (A) in premises A is expressed as:

$$F_{ldA}^{in}P(k) = \left( \varepsilon_{pvA-ldA}(k) \times P_{ldA}(k) \right) + \left( \varepsilon_{batA-ldA}(k) \times P_{ldA}(k) \right) + \left( \varepsilon_{grd-ldA}(k) \times P_{ldA}(k) \right)$$

Power flowing into load (B) in premises B is given as:

$$F_{ldB}^{in}P(k) = \left( \varepsilon_{pvB-ldB}(k) \times P_{ldB}(k) \right) + \left( \varepsilon_{batB-ldB}(k) \times P_{ldB}(k) \right) + \left( \varepsilon_{grd-ldB}(k) \times P_{ldB}(k) \right)$$

This model was simulated using MATLAB. An energy transfer from system B to system A was noted which is exactly the same as the result shown in Figure 5.

### 4.3 Simplicity and Flexibility of E-Variable Approach

The e-variable method will now be used to solve the problem in which introduction of a simple constraint to the EMS complicate the flowchart representation of the EMS as shown in Figures 8, 9 and 10. The first thing to consider is the definition of e-variable to the newly established connection i.e. between battery (B) in premises B and the grid. Secondly, the constraints imposed are going to be used to activate/deactivate the connection and then finally, the scenarios under which battery charging will occur. Therefore, based on the above factors, e-variables are expressed: First, the availability and requirement conditions for the interconnection between the grid and the battery in premises B are defined,  $P_{grd-batB}$ .

It is assumed that the power from the grid is always available and based on this assumption, the availability condition here is neglected. The requirement conditions between the grid and the battery are divided into four and are expressed as:

$$\varepsilon_{grd-batB}^{req}1(k) = (soc_{batB}(k) < 0.8) \wedge (0 \leq k \leq 10) \wedge (P_{netA}(k) < 0) \wedge (P_{netB}(k) < 0)$$

$$\varepsilon_{grd-batB}^{req}2(k) = (soc_{batB}(k) < 0.8) \wedge (0 \leq k \leq 10) \wedge (P_{netA}(k) > 0) \wedge (P_{netB}(k) > 0)$$

$$\varepsilon_{grd-batB}^{req}3(k) = (soc_{batB}(k) < 0.8) \wedge (0 \leq k \leq 10) \wedge (P_{netA}(k) < 0) \wedge (P_{netB}(k) > 0)$$

$$\varepsilon_{grd-batB}^{req}4(k) = (soc_{batB}(k) < 0.8) \wedge (0 \leq k \leq 10) \wedge (P_{netA}(k) > 0) \wedge (P_{netB}(k) < 0)$$

$$\varepsilon_{grd-batB}^{req}(k) = OR(\varepsilon_{grd-batB}^{req}1(k), \varepsilon_{grd-batB}^{req}2(k), \varepsilon_{grd-batB}^{req}3(k), \varepsilon_{grd-batB}^{req}4(k))$$

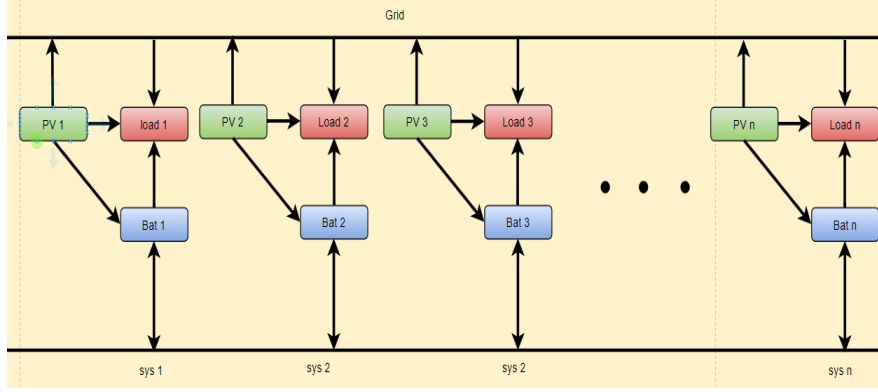


Figure 11: Block diagram model for P2P energy sharing with  $N$  peers

This adjustment is far more organized and systematic to make on the system than the previous one. There is a clear distinction of how complexity affects the system for both approaches and for this reason the e-variable would be suitable for modelling complex P2P systems. One of its key feature is that it remain simple regardless of the complexity of a system or the need to modify the EMS during operation.

#### 4.4 Modelling P2P Energy Sharing with $N$ -Peers using E-Variable

Now having looked at a system with two peers, a system with multiple peers of any number will be considered. There are  $N$  households considered here: premises 1 (sys 1), premises 2 (sys 2), premises 3 (sys 3) up to premises  $N$  (sys  $N$ ). Each system has a PV-battery system consisting of a PV-panel, a battery, and the local load at the premises. Figure 11 shows a block diagram modelling power flows for the system if P2P energy sharing is enabled.

The e-variables for the interconnections are defined as:

a)  $P_{pvn-ldn}$

The connection between the local load and the PV in premises  $n$  will be activated whenever the availability and requirement conditions are met simultaneously, else otherwise. The availability condition is that  $PV_n$  produce some amount of energy that is above zero at a particular instant  $k$  (i.e. sufficient sunlight that triggers energy conversion) and is expressed as:

$$\varepsilon_{pvn-ldn}^{avl}(k) = P_{pvn}(k) > 0$$

Similarly, the requirement conditions for this connection are divided into two ( $\varepsilon_{pvn-ldn}^{req}1(k)$  and  $\varepsilon_{pvn-ldn}^{req}2(k)$ ) depending on the logical constraint imposed by the EMS. The first requirement is that the net power in all the considered premises are simultaneously greater than zero at same instant or the net power in all premises are greater than zero except the last (say  $N$ ), which have its net power below zero at same moment. The second part of the requirement condition is that the net power in all premises are simultaneously less than zero or the net power in all premises are less than zero except the last (premises  $N$ ), which is greater than zero at same instant. Whenever the availability and requirement conditions are true the corresponding connection will be activated thus allowing power flow. These conditions are expressed in the following notations:

$$\varepsilon_{pvn-ldn}^{req}1(k) = ((P_{netn}(k) > 0) \wedge (P_{net(n+1)}(k) > 0) \wedge \dots \wedge (P_{netN}(k) > 0)) \vee (P_{netn}(k) > 0) \wedge (P_{net(n+1)}(k) > 0) \wedge \dots \wedge (P_{netN}(k) < 0)$$

$$\varepsilon_{pvn-ldn}^{req}2(k) = ((P_{netn}(k) < 0) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (P_{netN}(k) < 0)) \vee (P_{netn}(k) > 0) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (P_{netN}(k) > 0)$$

$$\varepsilon_{pvn-ldn}1(k) = (\varepsilon_{pvn-ldn}^{avl}(k) \wedge \varepsilon_{pvn-ldn}^{req}1(k))$$

$$\varepsilon_{pvn-ldn}2(k) = (\varepsilon_{pvn-ldn}^{avl}(k) \wedge \varepsilon_{pvn-ldn}^{req}2(k))$$

b)  $P_{pvn-grd}$

$$\varepsilon_{pvn-grd}^{avl}(k) = P_{netn}(k) > 0$$

$$\varepsilon_{pvn-grd}^{req}(k) = (socbat1(k) > 0.8) \wedge (P_{net(n+1)}(k) > 0) \wedge (socbat(n+1)(k) > 0.8) \wedge \dots \wedge (P_{netN}(k) > 0) \wedge (socbatN(k) > 0.8)$$

$$\varepsilon_{pvn-ldn}(k) = \left( \varepsilon_{pvn-grd}^{avl}(k) \wedge \varepsilon_{pvn-grd}^{req}(k) \right)$$

c)  $P_{grd-ldn}$

It is assumed that the power from the grid is always available and based on this assumption the availability condition here is neglected.

$$\varepsilon_{grd-ldn}^{req}1(k) = (P_{netn}(k) < 0) \wedge (socbatn(k) < 0.3) \wedge (P_{net(n+1)}(k) < 0 \wedge \dots \wedge (P_{netN}(k) < 0))$$

$$\varepsilon_{grd-ldn}^{req}2(k) = (P_{netn}(k) < 0) \wedge (socbatn(k) < 0.3) \wedge (P_{net(n+1)}(k) > 0) \wedge (socbat(n+1)(k) < 0.8 \wedge \dots \wedge (P_{netN}(k) < 0))$$

$$\varepsilon_{grd-ldn}^{req}m(k) = (P_{netn}(k) < 0) \wedge (socbatn(k) < 0.3) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (socbatN(k) < 0.8) \wedge (P_{netN}(k) > 0)$$

$$\varepsilon_{grd-ldn}1(k) = \varepsilon_{grd-ldn}^{req}1(k)$$

$$\varepsilon_{grd-ldn}2(k) = \varepsilon_{grd-ldn}^{req}2(k)$$

$$\varepsilon_{grd-ldn}m(k) = \varepsilon_{grd-ldn}^{req}m(k)$$

d)  $P_{pvn-batn}$

$$\varepsilon_{pvn-batn}^{avl}(k) = P_{netn}(k) > 0$$

$$\varepsilon_{pvn-batn}^{req}1(k) = (socbatn(k) < 0.8) \wedge (P_{net(n+1)}(k) > 0) \wedge \dots \wedge (P_{netN}(k) > 0)$$

$$\varepsilon_{pvn-batn}^{req}2(k) = (socbatn(k) < 0.8) \wedge (P_{net(n+1)}(k) > 0) \wedge \dots \wedge (P_{netN}(k) < 0)$$

$$\varepsilon_{pvn-batn}^{req}m(k) = (socbatn(k) < 0.8) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (P_{netN}(k) < 0)$$

$$\varepsilon_{pvn-batn}1(k) = \left( \varepsilon_{pvn-batn}^{avl}(k) \wedge \varepsilon_{pvn-batn}^{req}1(k) \right)$$

$$\varepsilon_{pvn-batn}2(k) = \left( \varepsilon_{pvn-batn}^{avl}(k) \wedge \varepsilon_{pvn-batn}^{req}2(k) \right)$$

$$\varepsilon_{pvn-batn}m(k) = \left( \varepsilon_{pvn-batn}^{avl}(k) \wedge \varepsilon_{pvn-batn}^{req}m(k) \right)$$

e)  $P_{batn-ldn}$

$$\varepsilon_{batn-ldn}^{avl}(k) = socbatn(k) > 0.3$$

$$\varepsilon_{batn-ldn}^{req}1(k) = (P_{netn}(k) < 0) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (P_{netN}(k) < 0)$$

$$\varepsilon_{batn-ldn}^{req}2(k) = (P_{netn}(k) < 0) \wedge (P_{net(n+1)}(k) < 0) \wedge \dots \wedge (P_{netN}(k) > 0)$$

$$\varepsilon_{batn-ldn}^{req}m(k) = (P_{netn}(k) < 0) \wedge (P_{net(n+1)}(k) > 0) \wedge \dots \wedge (P_{netN}(k) > 0)$$

$$\varepsilon_{batn-ldn}1(k) = \left( \varepsilon_{batn-ldn}^{avl}(k) \wedge \varepsilon_{batn-ldn}^{req}1(k) \right)$$

$$\varepsilon_{batn-ldn}2(k) = \left( \varepsilon_{batn-ldn}^{avl}(k) \wedge \varepsilon_{batn-ldn}^{req}2(k) \right)$$

$$\varepsilon_{batn-ldn}m(k) = \left( \varepsilon_{batn-ldn}^{avl}(k) \wedge \varepsilon_{batn-ldn}^{req}m(k) \right)$$

f)  $P_{batn-bat(n+1)}$

$$\varepsilon_{batn-bat(n+1)}^{avl}(k) = socbat1(k) > 0.8$$

$$\varepsilon_{batn-bat(n+1)}^{req}(k) = (P_{netn}(k) > 0) \wedge (P_{net(n+1)}(k) < 0) \wedge (socbat(n+1)(k) < 0.3)$$

$$\varepsilon_{batn-bat(n+1)}(k) = \left( \varepsilon_{batn-bat(n+1)}^{avl}(k) \wedge \varepsilon_{batn-bat(n+1)}^{req}(k) \right)$$

g)  $P_{batn-batN}$

$$\varepsilon_{batn-batN}^{avl}(k) = socbat1(k) > 0.8$$

$$\varepsilon_{batn-batN}^{req}(k) = (P_{netn}(k) > 0) \wedge (P_{netN}(k) < 0) \wedge (socbatN(k) < 0.3)$$

$$\varepsilon_{batn-batN}(k) = \left( \varepsilon_{batn-batN}^{avl}(k) \wedge \varepsilon_{batn-batN}^{req}(k) \right)$$

Power flowing into any battery can be calculated as:

$$F_{batA}^{in}P(k) = \sum_l^N (\varepsilon_{l-batA}(k) \times F_{l-batA}^{out}P(k)) \quad (8)$$

Likewise, the state of charge of any battery in the system can be calculated at any instant  $k$  by Equation (3)

$$SOCBat(k+1) = SOCBat(k) + \frac{F_{1-N}^{in}(k) - F_{N-1}^{out}(k)}{C_N}$$

It should be noted that the above definition is for a single system ( $N$ ). Each premises in the P2P scheme system needs a separate definition. If there are  $n$  households then  $n$  definitions will be needed for each.

## 5. CONCLUSION

In this paper, we presented a systemic approach to model the EMS of a grid-connected energy system undergoing P2P energy sharing. It allows the EMS representation to be feasible when the system scales up or imposes new constraints. The approach is based on state-space control theory where EMS was modelled using a combination of logical and relational operators. This strategy greatly enhanced the system's operation as it allowed to model, implement, enhance complicated EMS and offer a better insight into the system. We also demonstrated that this approach could be used in a P2P case study, where particular attention is drawn on reconfiguring the network or the EMS. We demonstrated that by using such method, it would be very easy to add and remove assets or modify the EMS. Furthermore, we compared the approach with a traditional "if-else" or flowchart approach. As a case study, we initially considered only two houses that have PV and batteries and then we scaled up the number of peers to  $n$ -peers, where  $n$  is the number of peers.

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