Maximisation of self-consumption of PV power

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1 Introduction

2 Problem statement

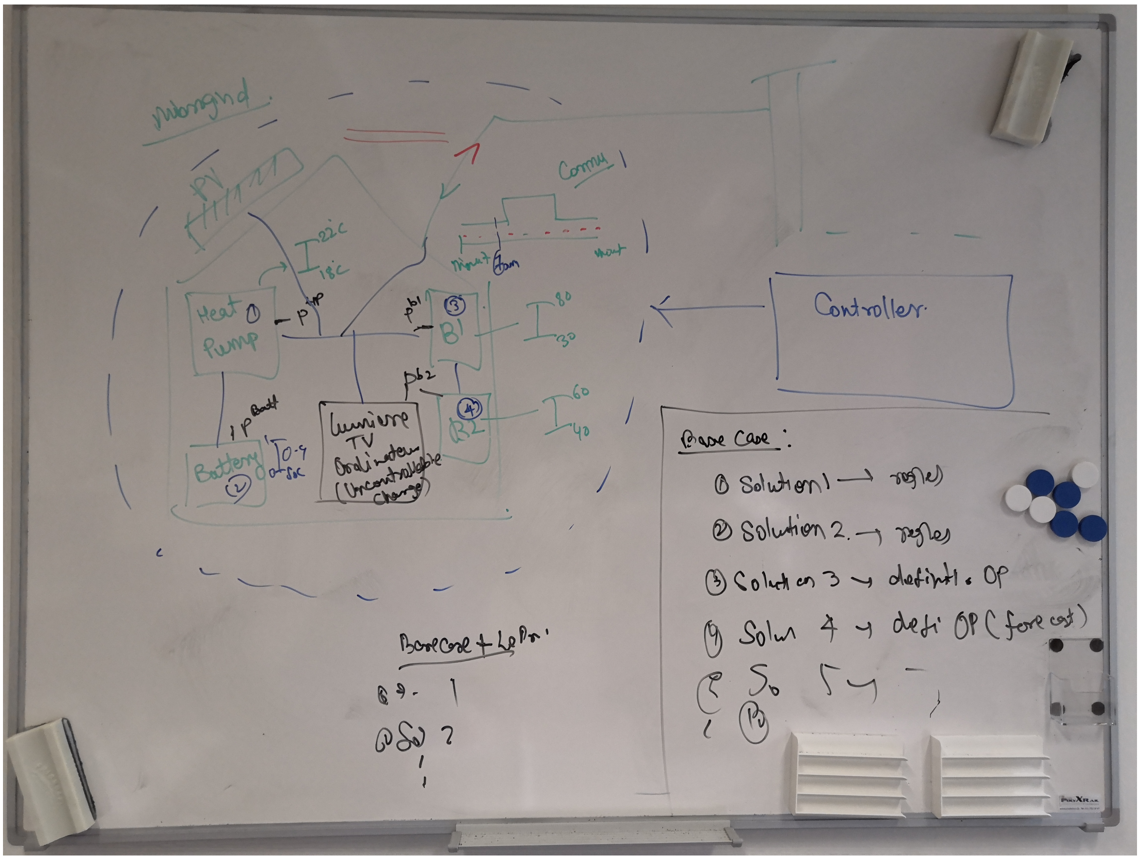

Figure 1: Microgrid sketch (to be changed afterwards)

2.1 System description

The object of the study is a microgrid connected to the distribution grid. In the present case, we consider a simple microgrid that can be seen as a domestic household equipped with a PV system. Because of its power generation capacity, the microgrid can inject excess power into the grid via a single two-ways connection.

As for the energy consumption of the household, this one can be divided in two well defined classes: controllable and non-controllable loads. The latter describes all appliances that are human-switched (TV, lights, coffee machine, etc.). The former makes reference to those flexible loads that are going to be controlled in order to consume whenever there is PV production. For instance, to ensure thermal comfort, the household is equipped with two boilers and a heat pump (HP). Also, an energy storage system (battery) is bringing more flexibility to the microgrid.

The objective of the energy management strategy is to control the flexible loads in order to reduce electricity costs by maximising self-consumption.

2.2 Modelling of the various components

The defined control strategies of the energy management system will handles discrete quantities.From 0 to H, the index h refers to current time period.

PV system

p_{PV}: PV output power after inverter's MPPT algorithm.

Energy storage system

Control variable (s):

u_b: Battery power (kW). Negative if battery is charging, positive if discharging. Or the opposite, don't know yet

Measured parameters:

$p_b^{measured}$: Measured battery power
x_b: Battery charge state (kWh)

Constant parameters:

$\overline{C}_b$: Max. battery capacity (kWh)
$\underline{C}_b$: Min. battery capacity (kWh)
$\overline{P}_b$: Max. charging power of the battery (kW)
$\underline{P}_b$: Max. discharging power of the battery (kW)

The variable u_b (kW) influences the State-Of-Charge (SOC) of the battery:

$$x_b[h+1] = (x_b[h] + u_b^+[h] + u_b^-[h])\,dt \tag{1}$$

$$u_b[h] = u_b^+[h] + u_b^-[h] \tag{2}$$

Battery charging/discharging power and capacity are physically limited. In order to ensure that $u_b^+[h]$ and $u_b^-[h]$ are not simultaneously non-null, binary variables s_b[h] are injected in the constraints:

$$\underline{C}_b \leq x_b[h] \leq \overline{C}_b \tag{3}$$
$$0 \leq u_b^+[h] \leq s_b[h]\, \overline{P}_b \tag{4}$$
$$0 \geq u_b^-[h] \geq (1 - s_b[h])\, \underline{P}_b \tag{5}$$

Initialization:

To avoid any distortion of results, the amount of energy stored within the battery at the initial time-step must be set as equal to the last:

$$x_b[0] = x_b[H] \tag{6}$$

Open parenthesis More accurate battery model for further study:

(α_b: Battery leakage coefficient (s^{-1}))
(η_b^+,η_b^-: Battery charging and discharging efficiency)

The continuous variable u_b (kW) influences the State-Of-Charge (SOC) of the battery. An integrative model describes the SOC evolution [**?**]:

$$x_b[h+1] = (\alpha_b\, x_b[h] + \eta_b^+\, u_b^+[h] + \frac{1}{\eta_b^-}\, u_b^-[h])\, dt \tag{7}$$
$$\tag{8}$$

Close parenthesis

Thermo-electric loads

The storage capacity from thermo-electric units, like electric boilers (B) and heat pumps (HP), allows operating them with certain freedom. Hence they can be employed under certain coordination, to actively respond to the power system fluctuations.

$\underline{P}^{B,k}$ Min. power of electric boiler k (kW)
$\overline{P}^{B,k}$ Max. power of electric boiler k (kW)
$\underline{P}^{HP}$ Min. power of electric heat pump (kW)
$\overline{P}^{HP}$ Max. power of electric heat pump (kW)

$$\underline{P}^{B,k} \leq p^{B,k}[h] \leq \overline{P}^{B,k} \tag{9}$$
$$\underline{P}^{HP} \leq p^{HP}[h] \leq \overline{P}^{HP} \tag{10}$$
$$\tag{11}$$

(For future extension of the problem set and for syntax purposes, it would be nicer to define a power vector $\hat{\boldsymbol{p}}^{\mathbf{c}}[h]$ for all the N_c controllable thermo-electric units. But maybe mixing B and HP will complicate things in MPC when handling with hot water consumption forecasts and outside temperature forecasts.)

Building comfort constraint must be respected and indoor temperature $T[h]$ must remain within a band around min and max temperature bounds ($\underline{T}$, $\overline{T}$). When the system temperature approaches one of the bounds (with an certain tolerance ϵ_T). Let's also define the target temperature T^{set} as $\frac{\underline{T}+\overline{T}}{2}$.

As for the boilers, flexibility is again achieved by imposing upper and lower limits to the hot-water temperature ($\underline{T}^{B,k}$, $\overline{T}^{B,k}$). Power injections into the thermo-electric units are also constrained:

$$p^{B,k}[h] \leq \overline{P}^{B,k} \tag{12}$$

$$p^{HP}[h] \leq \overline{P}^{HP} \tag{13}$$

$$\tag{14}$$

The structure/vector $\hat{\boldsymbol{x}}^{\boldsymbol{c}}[h]$ regroups the state of the N_c controllable thermo-electric units. From a controller device perspective, it is assumed that a pre-processing unit is handling thermal sensors outputs and normalizing them according to upper and lower limits of each load.

3 Control strategy

3.1 Principles

$C[h]$ is a global variable, known by the control system.

The microgrid automatically balances power supply and demand. We assume any PV generated power not consumed by the building is absorbed by the grid without the necessity of any control action. Similarly, any power demand from loads that cannot be supplied by the PV system is supplied by the grid.

The following control strategy is designed to manage controllable (flexible) loads. Hence, only five control variables are in play : s_b, u_b, $p^{B,k}$, p^{HP}.

3.2 Strategy 1

This being the first and most basic strategy, it does not demand models for thermo-electric units. In a straightforward manner, the charging of those flexible loads is done whenever lower temperature limits are attained. Measurements of power inputs are therefore not needed in this approach, and temperatures are the only variables used to determine the adequate control action.

The controller is configured by establishing rules determined by all possible system operating scenarios. Those logic constraints are:

1 - For feeding uncontrollable loads, PV power is the prior source, followed by battery storage and finally the main grid.

2 - As the only internal power generation source, PV system feeds storage battery and controllable loads with certain priority rules:

2.1 - ESBS has priority until 80% SOC is reached. An hysteresis' type control charges the battery until 80% SOC and lets it progressively discharge until 70% SOC.

2.2. Second in the priority ladder, controllable loads with the lower energy levels (normalized) are charged.

The variable $p_x = p_{PV} - p_{nc}$ refers to the excess PV power in the microgrid available to feed controllable loads. When such excess is negative, charging such loads demands electricity from the main grid.

Algorithm 1: : Lower constraint handling

Executed every time-step h
Inputs: $x_b[h-1], x_b[h], T_{B1}[h], T_{B2}[h], T_{HP}[h], p_{PV}[h], p_{nc}[h]$, Control variables: p_{B1}, p_{B2}, p_{HP} or just $\hat{\boldsymbol{p}}^{\boldsymbol{c}}[h]$
start
$p_x = p_{PV}[h] - p_{nc}[h]$
for *each energy system k in (B1, B2, HP)* **do**
    if $T^k[h] \in [\underline{T}^k; \underline{T}^k + \epsilon_T^k]$ **then**
        if $p_x > 0$ **then**
            $p^k \leftarrow min(p_x, \overline{P}^k)$
            if $(p_x > p^k)$ **then**
                $p_x = p_x - \overline{P}^k$
            end
        else
            $p^k \leftarrow \overline{P}^k$
        end
    end
end
update Control variables
call Algorithm 2 $(p_x, x_b[h-1], x_b[h], T_{B1}[h], T_{B2}[h], T_{HP}[h])$

We could handle the excess/surplus inside the constraint loop, but easier visualization if we present a second Algorithm for doing so:

Algorithm 2: : Treatment of microgrid's excess power

```
Executed for the time-step h
Inputs: p_x, x_b[h-1], x_b[h], T_B1[h], T_B2[h], T_HP[h]  Control variables: u_b, s_b, p_B, p_HP
diff_b = p_x - p_b[h]
if p_x > 0 then
    if (x_b[h] < 0.8(C̄_b - C_b)) and (u_b[h-1] > 0) then
        u_b ← min(u_b[h-1] + diff_b, P̄_b, (1/dt)(C̄_b - x_b[h]))
        (unconstrained, power constrained, energy constrained)
        p_x = p_x - u_b
        if p_x > 0 then
            call PriorityChargingFlexibleLoads(p_x) (Algorithm 3)
            break
        end
        else
            u_b ← 0
        end
    end
    if (x_b[h] > 0.7(C̄_b - C_b)) and (u_b[h-1] ≤ 0) then
        call PriorityChargingFlexibleLoads(p_x) (Algorithm 3)
    end
end
else
    u_b ← max(u_b[h-1] + diff_b, P_b, (1/dt)(C̄_b - x_b[h]))
    (unconstrained, power constrained, energy constrained)
end
update Control variables
```

Algorithm 3: Controllable loads priority rules

```
Inputs: p_x[h], x̂^c[h]  Control variables: p̂^c[h]
normalize x̂^c[h]
sort x̂^c[h] in increasing order
for k ∈ N_c do
    if x_k^c ∈ [1 - ε_T^k; 1] then
        break;
    end
    p^k ← min(p_x, P̄^k)
    p_x = p_x - p^k
    if p_x ≤ 0 then
        break;
    end
end
```

3.3 Strategy 2: accounting for grid's electricity prices

When the "get ready" phase starts, if PV is at low power states, the battery and the controllable loads will be charged by the main grid.//

During high priced period, controller configuration will be back to normal.

Let’s define the maximum time t_c^b needed to charge the battery from the lowest energy level to the highest.

$$t_c^b = \frac{\overline{C}_b^k - \underline{C}_b^k}{\overline{P}_b}$$

In the same way, $t_c^{B,k}$ and t_c^{HP} are maximum charging times for B and HP. The maximum time t_c needed to charge all appliances is hence defined as:

$$t_c = max(t_c^b, t_c^{B,k}, t_c^{HP})$$