Design of an Energy Management System for buildings: a bottom up approach

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1 Introduction

2 Problem statement

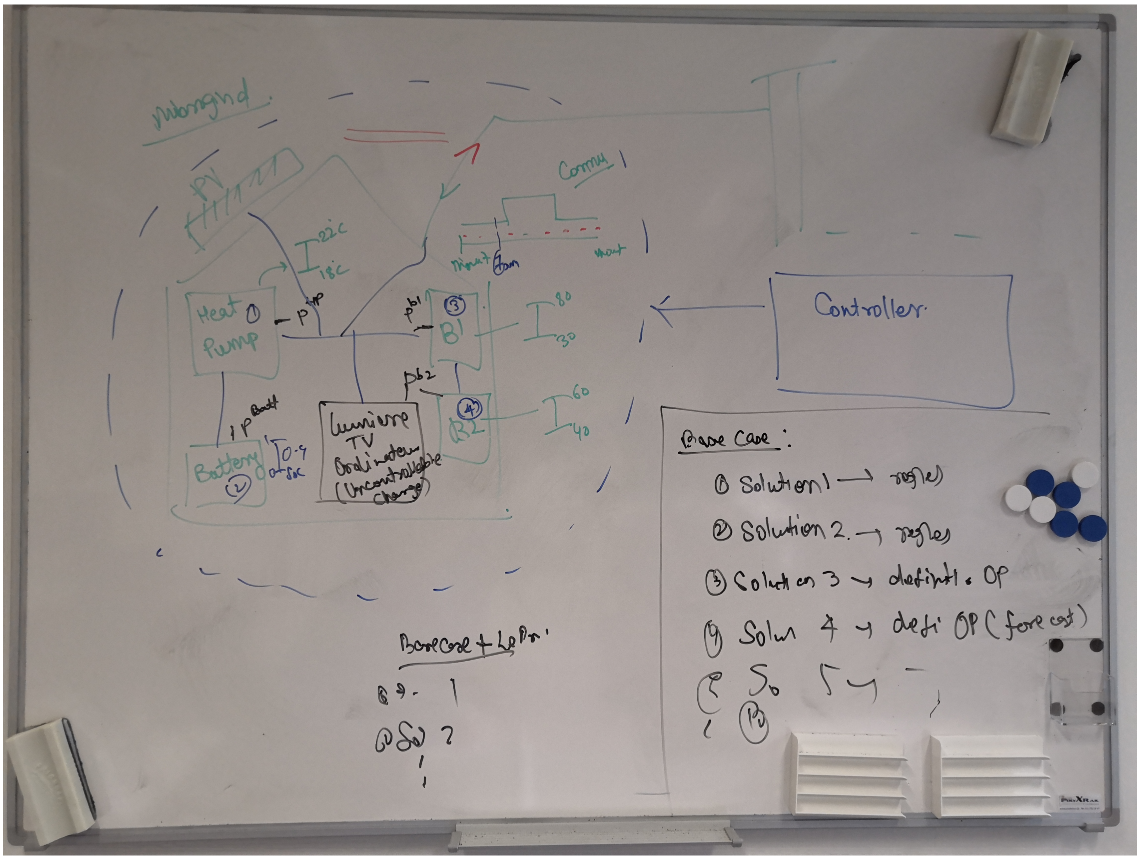

Figure 1: Microgrid sketch (to be changed)

A bottom up approach will be taken. The aim will be to start with a baseline scenario and progressively add up features and complexity to the system with the unique goal of reducing electricity costs. An analysis of the limitations and the drag downs of each of the added features will be carried.

3 Scenario 1

The first scenario describes the baseline case of a generic household. In order to produce locally and reduce its electricity bill, a PV system has been incorporated to the building. Now that it can also generate power and not only consume it as a load, the building can be seen as a grid-connected microgrid. In fact, the building can inject excess PV power into the grid via a single two-ways connection. Just as before the PV installation, the household can also consume from the grid whenever PV power is not enough to supply its different loads.

However, grid's electricity comes at a higher price. The feed-in tariff that the household gets for injecting power back to the grid is considerably lower than the cost of consuming electricity from such an unrestricted and reliable source. It is therefore the purpose of an Energy Management System (EMS) to maximise the self-consumption of PV power.

For that, the EMS has the ability to exploit the flexibility of the building. For instance, two electric boilers (B1 and B2) bring thermal storage capabilities to the household. An intelligent EMS would allow to operate those thermo-electric units under certain coordination to actively respond to the microgrid power fluctuations.

In this first scenario, the EMS objective is simply to take advantage of the flexibility of the two boilers. To ensure a certain hot-water supply, B1 and B2 should ideally be operated within min/max limits. Those two temperature ranges are the only degree of freedom for the EMS to operate. In contrast to the supply side which is non-controllable, the demand side can be controlled with the goal of matching PV production.

In a different category that boilers, the remaining household loads are non-controllable and represent another source of uncertainty. Those include lights, TV, washing machine and all human-switched appliances in general.

3.1 EMS Components and models

Regarding the EMS implementation, several features are needed. The physical quantities such as boiler temperatures and power consumed by the loads (boilers and non-controllable) need to be communicated to the controller, and same goes for PV generated power. In total, the EMS needs four additional power sensors and two temperature sensors. A communication layer is in charge of broadcasting sensors data to the centralized controller. This one processes such inputs and computes an adequate control action for each of the controllable units. The output is communicated back to the loads, where the actuator ensures that the controller orders are executed.

In order to actively control boilers 1 and 2, a model of such thermal loads has to be incorporated. To avoid over complicating scenario 1 and letting it as wide as possible, a very simplistic, linearly approximated model is used. The water's thermal capacity C_w describes its ability (and the boiler's) to accumulate heat. Ignoring all non-linearities and other factors such as hot-water consumption, the temperature development in the boiler is given by the differential Equation 1.

$$p_b^{elec} = C_w \frac{dT_w}{dt} \quad (1)$$

It is important to precise that the microgrid automatically balances power supply and demand. Under such assumption, any PV power not consumed by the building is absorbed by the grid without the necessity of any control action on the part of the EMS. Similarly, any power demand from loads that cannot be supplied by the PV system is supplied by the grid.

3.2 Notations

Control variables are named u, whereas measurement variables will be named p for load's power or x for load's state. Capital letters will designate constant parameters. Indexes will refer to specific energy systems. Time value of the variables will be noted with $[h]$, where h designates the current discrete time period of length dt, and goes from 0 to H. Regarding sign convention, a positive power refers to power that is injected into the microgrid, for instance by the PV system. A negative power is one that is absorbed by loads. Finally, underline ($\underline{\bullet}$) and overline ($\overline{\bullet}$) designate minimum and maximum values respectively and are subjected to the fiex sign convention.

PV system

p_{PV}: PV power (kW) (≥ 0)

Non-controllable loads

p_{nc}: power demanded by non-controllable loads (kW) (≤ 0)

Electric boilers

$u_{B,k}$: target power of boiler k (kW)
$p_{B,k}$: actual power of boiler k (kW)
$\overline{P}_{B,k}$: Max. power of boiler k (kW) (≤ 0)
$[\underline{T}_{B,k}; \overline{T}_{B,k}]$: lower and uppers limits on boiler's k hot-water temperature.
$T_{B,k}$: actual temperature of boiler k (°C)

Vectors $\hat{\boldsymbol{T}}_{\boldsymbol{B}}[h]$ and $\hat{\boldsymbol{u}}_{\boldsymbol{B}}$ regroup information of both boilers.

3.3 Control algorithm

The controller is configured by establishing rules determined by all possible system operating scenarios.

First, if the state of boilers is under or at the minimum limits $\underline{T}_{B,k}$, those are immediately supplied with power.
Then, PV generation is taking into account and managed according a simple priority ladder. PV power is first used to feed non-controllable loads p_{nc}. If PV power is enough to supply the building's non-controllable loads, the variable $p_x = p_{PV} + p_{nc}$ refers to the excess free power in the microgrid available to feed flexible loads. Those come second in the PV priority ladder, and the boiler with the lower normalized energy state

will be prioritize over its neighbour. Assuming that the controller knows the different temperature limits, it is able to normalize the measured temperature according to those values and compare both boiler states.

When there is no excess power, the supply of non-controllable loads in insured by the grid.

Boilers temperature evolution is defined in Equation 1 as a first order system. Controlling B1 and B2 hot water temperatures can be therefore performed by a simple proportional controller that acts on the error $e_k[h] = \overline{T}_{B,k} - T_{B,k}[h]$ (actual value - target value).

3.3.1 Pseudocode

Algorithm 1: Scenario 1: control of boilers

Executed every time-step h
Inputs: $\hat{\boldsymbol{T}}_{\boldsymbol{B}}[h], p_{PV}[h], p_{nc}[h]$
Control variables: $\hat{\boldsymbol{u}}_{\boldsymbol{B}}$
Initialize: $\hat{\boldsymbol{u}}_{\boldsymbol{B}} \leftarrow 0$

$p_x = max(0, p_{PV}[h] + p_{nc}[h])$
sort normalized $\hat{\boldsymbol{T}}_{\boldsymbol{B}}[h]$ in ascending order
for each boiler k **do**
  $e_k[h] = max(0, \overline{T}_{B,k} - T_{B,k}[h])$
  if $T_{B,k} \leq \underline{T}_{B,k}$ **then**
    $u_{B,k} \leftarrow \overline{P}_k$
    $p_x = p_x + u_{B,k}$
  else
    $u_{B,k} \leftarrow -min[C_w \frac{e_k[h]}{dt}, (-\overline{P}_k), p_x]$
    $p_x = p_x + u_k$
  end
end
update Control variables
end

3.4 Limitations

4 Scenario 2

Scenario 1 proposed the base layer to profit from the building's PV installation. By adapting demand to supply, self-consumption could be maximised and therefore power demanded to the grid was reduced. However, at moments when boilers are fully powered or at maximum temperature, some excess power may be re-injected into the grid and therefore wasted.

A first solution to that inconvenience is to install into the building an energy storage battery system. This will add a level of flexibility to the microgrid and will be able to shape the power system fluctuations by both consuming and producing power.

Because the battery is only going to step in after the flexible loads have offered their flexibility, a small battery is the most cost-effective solution. In fact, it is not needed to store all PV power, but rather to give to the microgrid that little extra self-consumption ability. Moreover, putting the battery last in the power supply priority is going to reduce pointless charge/discharge operations, which are the main source of aging/deterioration.

4.1 EMS Components and models

On top of the EMS architecture required for scenario 1, the incorporation of the battery adds some complexity to the microgrid.

It is assumed that the battery comes with its own software, and the designed EMS has to be able to adapt to it. Irrespective of the charge and discharge specificities of the battery software, the use of a simple model (Equation 2) allows to control its state. Charging and discharging efficiencies are assumed to be 100%, and no leakage phenomenon is considered.

$$x_b[h+1] = x_b[h] - p_b[h]\ dt \tag{2}$$
$$\underline{C}_b \leq x_b[h] \leq \overline{C}_b \tag{3}$$
$$\overline{P}_b^{ch} \leq p_b[h] \leq \overline{P}_b^{disch} \tag{4}$$
$$\tag{5}$$

New variables and parameters need to be addressed by the EMS. The battery's State-of-Charge x_b (kWh) and power p_b (kW) are measured and broadcasted to the controller. This one communicates back the target power u_b (kW) to be supplied or demanded to the storage system. Constant parameters are again assumed to be known by the controller. $\overline{C}_b$ and $\underline{C}_b$ are respectively the maximum and minimum battery capacity (kWh). Regarding power limits, $\overline{P}_b$ $(\leq\ 0)$ and $\underline{P}_b$ $(\geq\ 0)$ are respectively the maximum charging and maximum discharging battery power (kW).

Because model is linear, a simple proportional controller can also be used.

4.2 Control algorithm

The algorithm 1 presented in Scenario 1 is the backbone of the control strategy. A minor modification is needed to consider the battery. When boilers limits have been handled and excess power has been supplied to flexible loads, any remaining excess is going to charge the battery. On the other side, if PV power is not sufficient to power non-controllable loads, battery state is checked and storage is given the ability to cover that gap.

A detail worth mentioning is the fact that battery is not going to be supplying if boilers are at their lower limit. This is still an action exclusively supplied by excess power or eventually, grid power.

Algorithm 2: Scenario 2: control of boilers and battery

Executed every time-step h
Inputs: $\hat{\boldsymbol{T}}_{\boldsymbol{B}}[h], p_{PV}[h], p_{nc}[h], x_b[h], p_b[h]$
Control variables: $\hat{\boldsymbol{u}}_{\boldsymbol{B}}, u_b$
Initialize: $\hat{\boldsymbol{u}}_{\boldsymbol{B}} \leftarrow 0, u_b \leftarrow 0$

$p_x = p_{PV}[h] + p_{nc}[h]$
sort normalized $\hat{\boldsymbol{T}}^{\boldsymbol{B}}[h]$ in ascending order
for each boiler k **do**
    $e_k[h] = max[0, (\overline{T}_{B,k} - T_{B,k})]$
    if $T_{B,k} \leq \underline{T}_{B,k}$ **then**
        $u_{B,k} \leftarrow \overline{P}_{B,k}$
        $p_x = p_x + u_{B,k}$
    else
        if $p_x \geq 0$ **then**
            $u_{B,k} \leftarrow -min[C_w \frac{e_k[h]}{dt}, (-\overline{P}_k), p_x]$
            $p_x = p_x + u_k$
        end
    end
end
if $p_x \geq 0$ **then**
    $u_b \leftarrow max(\frac{x_b[h] - \overline{C}_b}{dt}, \overline{P}_b^{ch}, -p_x)$ (charging)
else
    $u_b \leftarrow min(\frac{x_b[h] - \underline{C}_b}{dt}, \overline{P}_b^{disch}, -p_x)$ (discharging)
end
update Control variables
end

4.3 Limitations

5 Scenario x

(nevermind)

In order to take into account the dynamics of boilers, a more detailed model than the one presented in Equation 1 is needed.

The hot water tank is modelled as a volume of water with a homogeneous temperature, across the whole tank. Its temperature variation is not only a function of the power input, but also of the hot-water consumption. The discretized equation can therefore be expressed as:

$$
\begin{aligned}
T_{wh}[h+1] = e^{-\frac{dt}{R_h C}}\; T_{wh}[h] + (1 - e^{-\frac{dt}{R_h C}})\; R_h\; u_{ewh}[h] \\
+ (1 - e^{-\frac{dt}{R_h C}})\; R_h\; \begin{bmatrix} U & d_w^h \end{bmatrix} \begin{bmatrix} T_a[h] \\ T_c[h] \end{bmatrix}
\end{aligned}
$$

where C is the water tank thermal capacity, $R_h = (U + d_w^h)^{-1}$ is the equivalent water-to-exterior resistance that takes into account the thermal losses U and water withdrawal d_w^h at time instant h. T_a and T_c stand for the ambient air temperature and the inlet cold water, respectively. The efficiency of the electrical system is assumed to be 1. d_w^k is the water drawn from the k^{th} hot water tank (l/s).