

Assignment 2021

Modeling and Control of Hybrid Systems (SC42075)

Delft Center for Systems and Control, Delft University of Technology

General remarks

- This assignment consists of two parts. In each part, several steps are outlined in a road map. You should follow this road map and present the results in a clear and concise report. In this report you should clearly explain and motivate all the choices you have made while solving the assignment.
In your report you should also add an **evaluation and conclusions section** of 1–1.5 pages, in which you briefly outline the main insights you have obtained while making this assignment. You should also add the Matlab files you have written in an *appendix* to the report.
- The deliverable of this assignment is a written report of max. 50 pages (including cover pages and appendices) about the assignment that also contains the *appendix* with your m files. Make sure to mention your group number and student number on the cover page. The report is to be uploaded as a single **pdf** file to **brightspace**.
The *hard* deadline for the report is Friday, June 18, 2021 at 17:00 p.m.
Please note that you will lose 0.5 point from your grade on the report for each (started) day of delay in case you exceed the deadline.
After uploading your report, please check it and make sure that you have submitted the correct file.
- You will be graded on the contents and the presentation of the report, on the originality¹ of your answers, and on the correctness, *efficiency*, and readability of the Matlab files (i.e., do not forget to include explanatory comments in your Matlab files).
- We recommend you to keep the computations symbolic or analytic as long as possible and not to hardcode any of the parameters in your Matlab programs (instead, write one separate Matlab function or script that defines the parameters) so that you can easily take other parameter values, longer control horizons, other reference signals, etc. into account.
Furthermore, since each step of this assignment depends on the preceding ones, we recommend that after Steps 2.2, 2.3, and 2.7 of the roadmap, you check your intermediate results with the teaching assistant (by email)². All other questions regarding this assignment should be asked via the Discussion Forum in Brightspace.

¹I.e., a correct answer that differs from the answers given by the other groups will be graded higher than a correct answer that is an almost literal copy of the answer of another group.

²The teaching assistant checks the overall picture and overall process only.

1 Part 1: Hybrid system example

Select a system in your own field of research, interests, or hobbies that can be considered as a hybrid system (and that has not yet been discussed in the lecture notes).

Step 1.1: Give a description of the system.

Step 1.2: Describe the system as a hybrid automaton (if needed, extend the definition of the (autonomous) hybrid automaton given in the lecture notes with inputs).

2 Part 2: Energy management of microgrids

Set-up

We consider a microgrid that is connected to the main power grid. Figure 1 presents a schematic diagram of the considered microgrid, where diesel generator (DG) units and their fuel tanks, batteries, and an energy management system (EMS) are the devices considered in this assignment. Assume that the EMS has an accurate prediction of the load in the microgrid and is able to communicate with the diesel generators and the batteries without any delay. We assume that the electrical connection between the microgrid and the power grid does not have any physical limit and, hence, the power balance of the microgrid can always be maintained. In other words, the amount of power used by the load and the charging batteries is equal to the power provided by the power grid, diesel generators, and the discharging batteries.

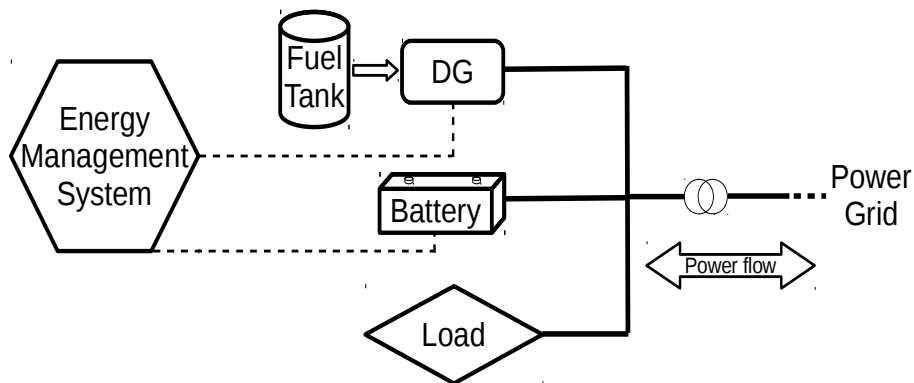


Figure 1: Schematic structure of the considered microgrid.

A price of electrical energy per kWh is defined for the exchanged energy between the microgrid and the power grid. As a result, whenever the electrical power is imported from the power grid, there is an additional operational cost of the microgrid due to the price of importing energy. Conversely, exporting energy to the power grid will result in a benefit for the microgrid. The energy management system is able to control the operation of the diesel generators and batteries and the aim of this road map is to design a hybrid model predictive controller for the energy management system such that the operational cost of the system is minimized.

Table 1: Parameters related to a battery

Variables related to a battery	Name	Range	Unit
Stored energy	x_b	$[0, \bar{x}_b]$	kWh
Exchanged power	u_b	$[\underline{u}_b, \bar{u}_b]$	kW
Operational mode (charge/discharge)	s_b	$\{0, 1\}$	–
Charging efficiency	η_c	CONSTANT	–
Discharging efficiency	η_d	CONSTANT	–

Tasks & Road map

Step 2.1: Modeling a battery

We consider a simple model for batteries, where a battery is considered as a storage of electrical energy with a different charging and discharging efficiency.

By considering the energy stored in the battery as the system state and using the variables of Table 1, construct a discrete-time piecewise affine (PWA) model of a battery. Note: The exchanged power of the battery denotes the charging/discharging power of the battery from the grid side and it can have a negative or positive sign. We consider a positive sign for the exchanged power whenever the battery is discharged, i.e., $s_b(k) = 0$. The sampling time of the system is expressed by T_s ³.

Step 2.2: Using the result of the previous step and the following constraints:

$$\begin{aligned}
 0 &\leq x_b(k) \leq \bar{x}_b \\
 \underline{u}_b &\leq u_b(k) \leq \bar{u}_b \\
 \text{if } s_b(k) = 1 &\Rightarrow u_b(k) \leq 0 \\
 \text{if } s_b(k) = 0 &\Rightarrow u_b(k) > 0,
 \end{aligned}$$

construct a mixed logical dynamical (MLD) model of a battery. Note: Determine the matrices $A, B_1, \dots, B_4, E_1, \dots, E_4, g_5$ in the following general MLD formulation:

$$\begin{aligned}
 x(k+1) &= Ax(k) + B_1u(k) + B_2\delta(k) + B_3z(k) + B_4 \\
 E_1x(k) + E_2u(k) + E_3\delta(k) + E_4z(k) &\leq g_5.
 \end{aligned}$$

Also indicate the definition of $x(k)$, $u(k)$, $\delta(k)$, and $z(k)$.

Step 2.3: Modeling a diesel generator

Suppose that the fuel consumption of the diesel generator can be determined by the following function⁴:

$$f(u_d(k)) = \begin{cases} u_d^2(k) + 4 & \text{if } 0 \leq u_d(k) < 2 \\
 4u_d(k) & \text{if } 2 \leq u_d(k) < 5 \\
 -9.44u_d^3(k) + 166.06u_d^2(k) - 948.22u_d(k) + 1790.28 & \text{if } 5 \leq u_d(k) < 7 \\
 -11.78u_d(k) + 132.44 & \text{if } 7 \leq u_d(k) < 9 \\
 4.01(u_d(k) - 10.47)^2 + 17.79 & \text{if } 9 \leq u_d(k) \leq 15, \end{cases}$$

³Please use all parameters in your model.

⁴Note that in this assignment we consider a fictional diesel generator.

Table 2: Parameters related to a diesel generator

Variables related to a diesel generator	Name	Range	Unit
Remaining fuel	x_d	$[\underline{x}_d, \bar{x}_d]$	kg
Generated power	u_d	$[0, \bar{u}_d]$	kW
Operational mode (on/off)	s_d	$\{0, 1\}$	–
Filling rate of fuel tank	R_f	CONSTANT	kg/h

where $f(u_d(k))$ is the consumed fuel of the diesel generator at time step k in [kg/h] and the value of $u_d(k)$ represents the output power of the diesel generator at time step k .

Construct a PWA approximation $\hat{f} : [0, \bar{u}_d] \rightarrow \mathbb{R}$ with 4 regions of the fuel consumption curve f as follows. The function \hat{f} is in the form

$$\hat{f}(u_d(k)) = \begin{cases} a_1 + b_1 u_d(k) & \text{if } 0 \leq u_d(k) < u_1 \\ a_2 + b_2 u_d(k) & \text{if } u_1 \leq u_d(k) < u_2 \\ a_3 + b_3 u_d(k) & \text{if } u_2 \leq u_d(k) < u_3 \\ a_4 + b_4 u_d(k) & \text{if } u_3 \leq u_d(k) \leq 15, \end{cases}$$

where $u_1 = 5$, $u_2 = 6.5$, and $u_3 = 11$. Determine a_i and b_i for $i \in \{1, 2, 3, 4\}$ such that the squared area between f and \hat{f} is minimized, or equivalently, such that:

$$\int_0^{\bar{u}_d} (f(u_d) - \hat{f}(u_d))^2 du_d$$

is minimized.

From now on, we consider the PWA function \hat{f} as the fuel consumption function of the diesel generator.

Step 2.4: Now consider that the values of u_1 , u_2 , and u_3 in Step 2.3 are not fixed. Determine the values of a_i and b_i for $i \in \{1, 2, 3, 4\}$ and u_j for $j \in \{1, 2, 3\}$ such that the squared area between f and \hat{f} is minimized.

Step 2.5: Consider a switching signal, s_d , that indicates the on/off operational mode of the generator. In addition, suppose that the fuel tank is constantly refilled with an amount R_f [kg/h]. By considering the fuel level in the tank, x_d , as the system state and using the result of Step 2.3, construct a discrete-time PWA model for the diesel generator.

Step 2.6: Using the results of the previous step and the following constraints:

$$\begin{aligned} \underline{x}_d &\leq x_d(k) \leq \bar{x}_d \\ 0 &\leq u_d(k) \leq \bar{u}_d \\ \text{if } s_d(k) = 0 &\Rightarrow \text{there is no power generation at time step } k, \end{aligned}$$

construct an MLD model of the diesel generator. Report your final result in the general MLD formulation as explained in Step 2.2.

Step 2.7: *System model*

Now consider the diesel generator of Step 2.3 and two batteries with the specifications described in Tables 3 and 4. Write a Matlab program to create the MLD model of a system that contains all the devices. From now on, assume that $T_s = 0.25$ [h].

Table 3: Specification of the batteries

Battery number	η_c	η_d	\bar{x}_b [kWh]	\underline{u}_b [kW]	\bar{u}_b [kW]
1	0.9	0.8	48	-3	2
2	0.95	0.77	64	-4	3

Table 4: Specification of the diesel generator

Parameter	Value
\underline{x}_d	20 [kg]
\bar{x}_d	120 [kg]
\bar{u}_d	15 [kW]
R_f	0.4 [kg/h]

Step 2.8: Defining the cost function

The operational cost of the microgrid at time step k is defined as:

$$\begin{aligned}
 J(k) = & \sum_{j=0}^{N_p-1} \left(\sum_{i=1}^{N_b} W_{b,i} |\Delta s_{b,i}(k+j)| + W_d |\Delta s_d(k+j)| \right) \\
 & - W_{\text{fuel}} (x_d(k+N_p) - x_d(k)) - W_e \sum_{i=1}^{N_b} (x_{b,i}(k+N_p) - x_{b,i}(k)) \\
 & + \sum_{j=0}^{N_p-1} P_{\text{imp}}(k+j) C_e(k+j),
 \end{aligned} \tag{1}$$

where $P_{\text{imp}}(k)$ is the imported power to the microgrid at time step k and $C_e(k)$ is the price (benefit) of importing electricity to (exporting electricity from) the microgrid at time step k . Given the fact that the power balance condition is always maintained, we have:

$$P_{\text{imp}}(k+j) = P_{\text{load}}(k+j) - u_d(k+j) - \sum_{i=1}^{N_b} u_{b,i}(k+j), \quad \forall j.$$

The parameter N_b determines the number of batteries in the microgrid. The weights in the cost function are given in Table 5. Note that for a signal $s(\cdot)$, we have $\Delta s(k) = s(k) - s(k-1)$.

Write a Matlab program that computes the optimal MPC input sequence for a given sample step k for any given values of N_p and N_c (i.e. the control horizon). Assume that the values of \tilde{C}_e and

Table 5: Value of the weight factors in the cost function

Weight factor	Value
$W_{b,i}$	$2+i$
W_d	10
W_{fuel}	4
W_e	0.4

\tilde{P}_{load} are known, where

$$\tilde{C}_e = [C_e(k) \quad \dots \quad C_e(k+N_p-1)]^T$$

$$\tilde{P}_{\text{load}}(k) = [P_{\text{load}}(k) \quad \dots \quad P_{\text{load}}(k+N_p-1)]^T.$$

Hints & notes:

- By introducing some dummy variables, an optimization problem of the form $\min_{\theta \in \mathbb{R}^n} \|\theta\|_1$ subject to $A\theta \leq b$ can be transformed into a linear programming (LP) problem:
 - Recall that for $\theta \in \mathbb{R}^n$, we have $\|\theta\|_1 = \sum_{i=1}^n |\theta_i|$. Now it is easy to verify that any optimal solution (ρ^*, θ^*) of the problem

$$\min_{\rho, \theta \in \mathbb{R}^n} \rho_1 + \dots + \rho_n \quad \text{subject to} \quad -\rho \leq \theta \leq \rho \quad \text{and} \quad A\theta \leq b$$

is also an optimal solution of $\min_{\theta \in \mathbb{R}^n} \|\theta\|_1$ subject to $A\theta \leq b$ (and vice versa if we set $\rho^* = \|\theta^*\|_1$).

- The MPC optimization problem at time step k can be transformed into a mixed-integer linear programming problem (MILP).
- In order to solve an MILP problem, you can use one of the following options:
 - Use the `glpk` function of the MPT toolbox version 3 (for MATLAB R2011a and newer) (see <https://www.mpt3.org/>)
 - Use the Matlab interface of the Gurobi optimizer. See: <https://www.gurobi.com/products/gurobi-optimizer/>
 - Use the `cplex` command of the TOMLAB cplex toolbox (note that you need a license, see <https://tomopt.com/tomlab/>). With this command you can solve MILP problems (see also the `milp_solve_tomlab_cplex` script on the course website).
- As we want you to get some insight into the hybrid MPC method and the relation with integer programming, you are *not* allowed to solve the entire exercise using the `mpt_control` or related commands of the MPT toolbox or the Hybrid Toolbox (see <http://cse.lab.imtlucca.it/~bemporad/hybrid/toolbox/>). However, feel free to compare the results obtained with your own programs to those obtained with the MPT toolbox or the Hybrid Toolbox, and to discuss the differences, if any.

Step 2.9: Write a Matlab program to simulate the closed-loop behavior of the system (i.e. apply the receding horizon approach in which at each step the optimal MPC control input is recomputed

and applied to the system). Assume that

$$N_p = N_c = 25$$

$$x_d(0) = 50$$

$$x_{b,i}(0) = 10, \forall i$$

$$s_d(-1) = s_{b,i}(-1) = 0, \forall i$$

$$C_e(k) = 50 + 50 \sin\left(\frac{\pi T_s k}{12}\right)$$

$$P_{\text{load}}(k) = \begin{cases} 0 & \text{if } k \leq 20 \\ 30 + 2k & \text{if } 21 \leq k \leq 50 \\ 45 & \text{if } k \geq 51 \end{cases}$$

Report your results.

Step 2.10: Now we want the state of charge of the batteries to be more than 20% at 12 AM and 12 PM every day. Express this goal in the form of some inequalities and simulate the system with the updated set of inequalities.⁵

Note: Do not forget to include in your report an evaluation and conclusions section of 1-1.5 pages, in which you briefly outline the main insights you have obtained while making this assignment.

⁵ The simulation time should be longer than 36h.