MODEL PREDICTIVE CONTROL BASED ENERGY MANAGEMENT OPTIMIZATION FOR A EUROPEAN MICROGRID IMPLEMENTATION

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ABSTRACT

This paper presents a case study of two approaches for optimal microgrid control. The simulations are based on a real test site located in Sweden. One of the two presented models replicates the actual implemented rule based control (RBC) that is currently realized on the test site. The second model applies a model predictive control (MPC) scheme assuming the same system and boundary conditions. The performance is assessed in terms of maximizing the islanding time, signifying the time the microgrid (MG) can disconnect from the remaining distribution grid.

INTRODUCTION

The optimal control of MGs under the influence of high shares of intermittent renewable energy sources (RES) and fluctuations on the demand side is one key challenge of a safe and reliable system operation.

This research is conducted to evaluate the interplay between energy market players in the distribution grid, integrating demand side response (DSR) on the customer side and an energy management system (EMS) on the system operator side.

The flexibility aspect is addressed through controllable RES, smaller residential and large system battery energy storages (BESS), as well as power-to-heat solutions such as heat pumps (HP) and hot water boilers (HWB) [1].

The E.ON demonstrator MG, of the H2020 InterFlex project is located in Simris and designed to be able to seamlessly switch between grid connected and islanded operation as well as the operation in a so called virtual island mode. The latter comprises grid situations in which the physical point of common coupling (PCC) to the overlying grid is active, while the actual energy exchange is close to zero.

The Swedish demonstrator MG provides the possibility to autonomously supply the network based on aforementioned flexible resources for several minutes to hours.

APPROACH

This paper describes the steps that have been taken in order to first understand the system setting and replicate the existing RBC. Secondly, it shows which aspects are to be analyzed to develop a suitable MPC scheme.

Requiring that the MPC should be easily implementable in the field, it is important that the resources, that require a high number of monitoring devices to provide sufficient input data, are reduced as much as possible.

This way, the underlying models for the assets reveal an approximate character which, on the one hand, might decrease the fitness of the MPC.

On the other hand, even with imperfect control models, the MPC might be more suitable than the RBC. Additionally the replicability of the developed model for other test sites is improved.

Performance Indicators for Comparison

To evaluate the performance and suitability of an empirically developed RBC in contrast to a comparably intricate MPC, following indicators have been selected:

- Number, type and accessibility of required data,
- Number of battery charging/discharging switches per day,
- Total amount of positive and negative energy exchange to the grid,
- Amount of energy that needs to be supplied by the backup generator (BUG),
- Total duration and period of virtual islanding mode.

The resulting indicators are highly dependent on the chosen testing conditions. In this study, an average load- and renewable energy generation situation is tested for the demonstrator.

SIMRIS TEST SITE

The demonstrator is fully operational leveraging on an empirically developed rule based EMS. A schematic representation of the MG test site in Sweden is given in **Figure 1**. The consecutively numbered dots i.e. on the network intersections each represent physically installed busses.

Assets Connected to the MV Grid

On the generator side, Simris offers favorable conditions for renewable energy sources which is why both, photovoltaic and wind generation systems are installed (see **Table 1**). Additionally, a diesel generator serves as a backup for critical grid situations.

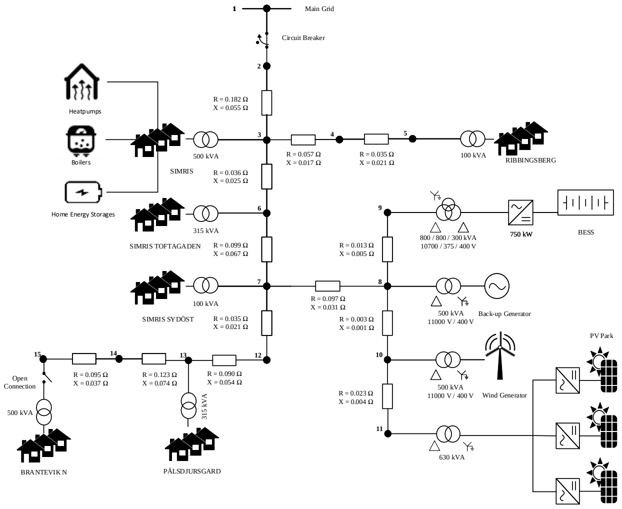

Figure 1 Schematic representation of the MG test site

Table 1 Parameters of the energy generating assets that are implemented in both models.

	Wind	PV	Diesel
Rated Power [kW]	500	442	350

To enhance the consumption of renewable energy locally, a Li-Ion BESS is installed at the MV grid. In early 2019 a redox flow BESS is installed in addition to the existing battery to be able to increase the islanding potential of the MG (see **Table 2**).

Table 2 Parameters of the large BESSs that are implemented in both models.

	Li-Ion	Redox Flow
Capacity [kWh]	333	1600
Min. SOC	0.2	0
Max. SOC	0.9	1
$\eta_{\text{(dis)charge}}$	0.92	0.775
Max Charge [kW]	1342.32	200
Max Discharge [kW]	839.02	200

Controlling the above mentioned assets on the MV level is part of the EMS.

Assets Connected to the LV Grid

The represented demonstration site comprises mainly single-family residential buildings on the load side with a total number of 150 customers connected to the LV grid. The characteristics of the loads do not reveal sharp load changes.

Since 2013, in the context of this research initiative, several households were equipped with a set of home energy storage and PV systems. The DSO is allowed to control the batteries for demand side response purposes.

In addition, some households allow the DSO to control their heat pumps for DSR as long as the controlled temperature does not deviate more than $\pm 1℃$ compared to the reference room temperature.

The third DSR element is provided by hot water boilers that serve for warm water control. In this case, the DSO is enabled to turn the boilers on and overheat the water temperature to increase the MG load. The most relevant figures concerning the described devices are given in **Table 3,** aggregated to one DSR asset per type.

Table 3 Parameters of the demand side response assets that are implemented in both models.

	DSR HP	DSR Boilers	DSR Batteries
Capacity [kWh]	48	58.15	36.4
Min. SOC	0.15	0.15	0.15
Max. SOC	1	1	0.9
$\eta_{\text{(dis)charge}}$	-	-	0.95
Max Charge [kW]	-	-	25.41
Max Discharge [kW]	-	-	35.97
cos φ	0.9	0.9	-
COP	3.5	0.95	-

Controlling these devices on the LV level is part of the DSR which is implemented as a subsystem of the EMS.

CONTROL OBJECTIVE & SCHEMES

The reference value for the RBC is the active power that is exchanged through the PCC, targeting a maximization of the virtual islanding period, which is the total time in which the active power at Bus 1 is equal to zero. The MPC combines several target functions in a multi-objective optimization.

Simulation Environment

Both models simulate the quasi-continuous behavior of the controllers.

The simulations are implemented in MATLAB Simulink while for the MPC optimization, which is formulated as a mixed integer second order cone problem, additionally the YALMIP toolbox [2] is combined with the GUROBI solver software [3]. The controller sample time is set to one hour, using a forecast horizon of 24 hours. The discrete time steps of equal length are taken to apply power flow constraints to the model [4][5].

Data Sources

The chosen dataset comprises load data at bus 1, 3, 5, 6, 7 and 13 as well as the measurements at the busses 8-10, mainly revealing information on the RES generation for the given period.

The dataset is provided in 10 minute resolution and is scaled accordingly to hourly time steps.

The simulation incorporates 72 consecutive hours from the 1st October to the 3rd October 2018.

Due to the lack of load data from Bus 5, 6, 7 and 13 for the chosen period, measurements, that have been collected in the previous year during the same season and for the same weekdays (Mon-Wed: 25.09.2017-27.09.2017) are taken instead for these substations.

For the thermal load, which is necessary to simulate the heat pump behavior in both models, load profiles were created based on 2010 German standard load profiles, scaled to the controllable thermal load capacity that is apparent on the test site.

The dimensioning of the annual thermal demand and device capacity derives from the open source TABULA WebTool [6], which requires building parameters such as typical size, height, location and age of the houses.

Rule Based Control

The RBC has been developed by the local distribution system operator in an empirical step by step approach.

In a first control level, the large BESS comprising the Li-Ion and the redox flow battery are in charge mode as long as $P_{Grid\ Exchange} < 0$, which implies a surplus of energy in the MG and vice versa.

The BUG is triggered as soon as the BESS SOC falls below 30%. The generator reference value is set back to zero for an SOC > 70%. Technically, the BUG then unloads over 30 seconds first before being able to disconnect from the grid.

On a second control level, depending on the SOC of the Li-Ion battery, the aggregated home energy storages are charging or discharging such that their SOCs match with the larger battery.

The heat pump as well as the hot water boilers also take the Li-Ion battery's SOC as the reference value for the DSR control. **Figure 2** gives an overview of the applied rules for the EMS and DSR control.

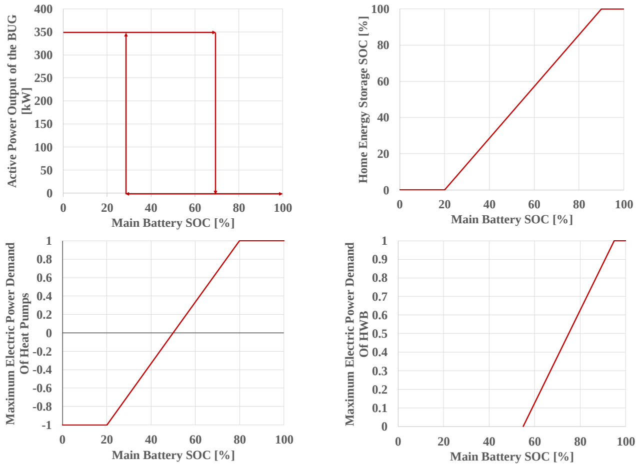

Figure 2 RBC overview in dependence of the BESS SOC

RES curtailment is also a lower priority option to balance the energy of the MG. In this case the RES are curtailed linearly starting at an SOC level of 90% and being fully curtailed at 95%.

Model Predictive Control

MPC solves control tasks optimally for a specified time horizon since it allows integrating technical system boundaries, a use case- specific objective function, and demand and supply forecast time series. The employed MPC repeatedly optimizes MG assets' active and reactive power set-points for a forecast horizon based on a receding window. This allows to respect updated forecasts of future load and RES behavior as well as concurrent measurements within the network and therefore helps to reject disturbances introduced by the uncertainty in resource forecasting.

Forecasting

Earlier studies have shown an advanced forecasting algorithm in the context of the presented MG demonstrator and the according influence of the related uncertainties on the MPC [1].

This paper presents results that have been generated using a perfect forecasting assumption in order to evaluate whether an MPC implementation would be preferable compared to the RBC independent from different forecasting approaches.

Applied Cost Factors

In contrast to the RBC, which neglects the energy price development, the MPC employs the cost factors for the energy exchange through the PCC as well as the operating cost of the BUG, since one factor within the objective function accounts for reducing the operational cost.

Although the actual price for the power that is feeding the MG through the PCC is dependent on multiple factors such as earlier agreed bi-lateral contracts as well as activities on the spot market, for the simulation, only day- ahead prices which apply to the demonstrator site (bidding area SE4) have been selected [7]. This allows to roughly replicate the hourly value for energy capacities for the chosen testing period.

Additionally, operational costs apply to the BUG such as the fuel price [8]. For 2018, the average Diesel price in Sweden amounts to 1.48€/l [9], which has been considered in the simulation.

Constraints

Earlier studies presented a detailed description of a possible constraint implementation for the MG devices [2]. The constraints mainly apply to the maximum and minimum active and reactive power output, maximum and minimum storage capacity (electrical and thermal) as well as charging and discharging power limits. In addition to the existing devices, the hot water boilers were introduced in this study. For this, the hot water boilers are modelled in accordance to the heat pump model.

Objective Function

This study follows the multi-objective optimization approach that has been presented in earlier work [10].

For the optimization a weighted linear combination of four separate minimization objectives is pursued:

- Cost for energy exchange + operational cost,
- Net energy exchange to the main grid,
- Potential disconnection time from the main grid starting one step in the future at t=t+1,
- Load flow related energy losses.

Each of the four objectives is first normalized so that each objective lies within the range of [0, 1] and can then be weighted individually to fit the aim of the operating party. The presented results show the outcome of the MPC simulation for equally weighted factors.

RESULTS

Required Data for MPC Development

In addition to the asset and grid information that is needed to develop a RBC the minimum requirement to implement an MPC is listed below:

1. Current and future electrical load,
2. Current and future RES generation,
3. Electric demand of heat pump and water boilers,
4. COP values of heat pumps and hot water boilers,
5. And the future energy price.

For a more detailed model, which incorporates forecast uncertainties i.e. based on a neural network based forecast algorithm, following additional requirements arise:

6. Forecasts for electric energy demand,
   - 6.1. An NN- based forecast would require load measurements of a time frame of several years.
7. Forecasts for renewable energy generation:
   - 7.1. Number, size and position of PV modules,
   - 7.2. Forecasts on future solar irradiation,
   - 7.3. Measurement of solar energy supply for a time frame of several years in correlation with solar irradiation,
   - 7.4. Number, size, height and position of wind generators,
   - 7.5. Forecasts on future wind speed and direction,
   - 7.6. Measurement of wind energy supply for a time frame of several years in correlation with according wind values.
8. Forecast values for thermal load per household (ambient temperature):
   - 8.1. Reference temperature settings,
   - 8.2. Internal control behavior of the heat pumps,
   - 8.3. Measurement of heat demand of the heat pumps for a time frame of several years,
   - 8.4. Measurement of outer temperature energy supply for a time frame of several years,
   - 8.5. Orientation of the building accompanied by appropriate solar irradiation measurement.
9. Room temperature and flow temperature measurement,
10. Heat transfer of the building,
11. Water tank level and tank temperature of the boilers,
12. Forecast values for thermal load per household (warm water temperature):
    - 12.1. Water draw profiles from past several years,
    - 12.2. Amount of persons living in households.

Requirement 8.5 allows to model the influence of external disturbances on the reference temperature which, when integrated in the control loop, inhibits overshoots of the controller temperature.

The data list reveals that a significant amount of information needs to be collected to be able to develop an accurate MPC algorithm, assuming that a centralized MPC is realized. For the majority of DSO’s this set of information is hardly accessible which could count against the feasibility of the MPC. However, even reasonable assessments, synthetic profiles, available data with possibly imperfect accuracy, etc. could be strategies to realize an MPC though not having perfect information.

General Comparison of the Control Strategies

The indicators in **Table 4** result from applying both models on the same testing conditions with the implemented data sources deriving from the demonstrator site in Simris and count for 72 consecutive hours of MG operation from early October 2018.

Table 4 Comparison of the MPC with regard to the RBC

	RBC	MPC
Number of BESS switching actions [kWh]	4	4
Energy capacity that has been exported to the main grid [MWh]	12,304	3,553
Energy capacity that has been imported from the HV grid [MWh]	15,542	23,693
Amount of energy that has been supplied by the BUG [MWh]	18.2	0
Longest period in virtual island mode [h]	9	9
Total time in virtual island mode [h]	28	13

Under chosen testing conditions, both models result in the same number of switching of BESS switching actions, i.e. the transitions from charging to discharging operation and vice versa. Future studies could account for minimizing switching frequencies for longer battery lifetime as part of the objective function of the MPC.

Figure 3 shows that the MPC discharges the main battery during a peak price period on the first day. According to **Table 4**, the BUG is not employed at all within the MPC based on higher fuel prices compared to the day ahead price that applies for energy exchange via the PCC.

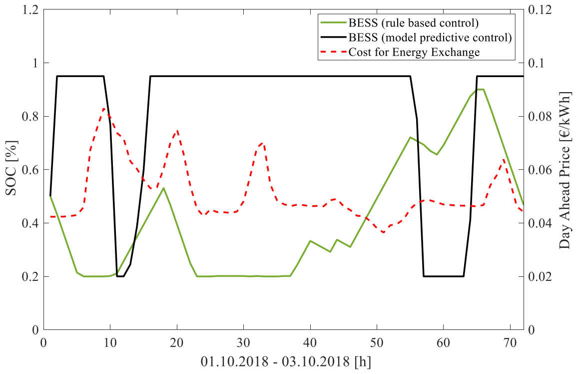

Figure 3 BESS SOC Profile with Day Ahead Prices

This results in larger capacities that are imported from the main grid and kept in the storage devices. This results from the two elements minimizing cost and potential reconnection for the next time step that are implemented in the multi-objective optimization.

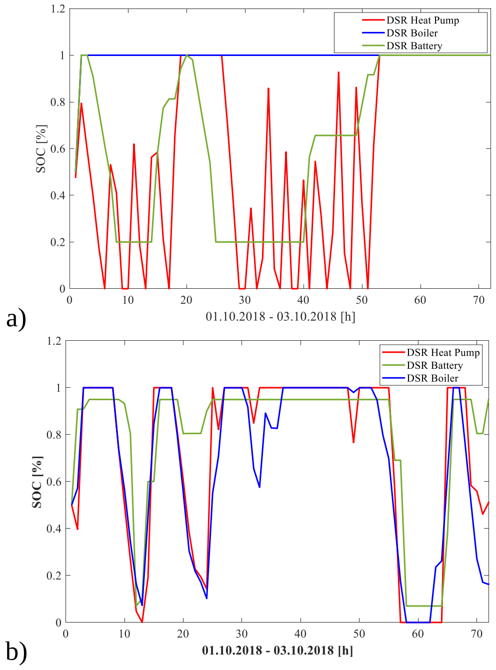

Figure 4a, 4b SOC development of the aggregated DSR elements under a) RBC and b) MPC

Figure 4a that, utilizing the described RBC setting, for the chosen testing period of 72 hours, frequent changes of the heat pump SOC occur.

The fact that the water boiler SOC does not change shows that at each time step the electric load resulting from the DSR is > 0 so that the SOC is not reduced by the thermal loss rate nor by any hot water consumption.

Overall, the DSR behavior of each device in the rule based case is different from each other, compared to the MPC. The DSR elements in the MPC, react more simultaneously and operate in the same load direction. This shows, that the considered control rules of the RBC have to be adjusted further step by step in order to achieve a more accurate response to system imbalances.

CONCLUSION AND OUTLOOK

This paper approached the assessment of two significantly different control strategies for a real MG test site. The presented first results, show that the control strategies deliver the expected outcome.

The RBC results in a longer time in virtual island mode, for the case that the factors of the objective function are equally weighted, since all control settings are set to minimize the energy exchange to the HV grid, regardless of possible high cost due to the operational cost of the activated BUG. When setting the cost factor to zero, the MPC achieves, an even higher total islanding time (33h) as well as longer period (17h) in islanding mode. Thus, showing that the MPC delivers accurate controller settings with regard to customized objectives, while the detailed results in **Table 4** compare the RBC to the MPC with equally weighted objectives only. The assessment shows the best case scenario for the MPC since perfect forecasting has been assumed.

The testing conditions and period could not be exhausted to an extent that the fitness of one control scheme compared to the other could be finally evaluated.

To achieve higher validity of the performance indication, a longer time frame needs to be analyzed as well as the impact of choosing a different test site, which has not been covered by the presented research. With longer simulation periods, information on asset degradation (battery, heat pump and boiler) could be gained. Also applying more detailed cost structures would make an economic comparison possible. Especially assessing the control scheme on different grid structures and assets, could ultimately clarify to what extent and under which conditions, the MPC is favourable to the RBC.

Therefore, future studies will focus on the scalability and replicability of the underlying models.

ACKNOWLEDGMENTS

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