A STUDY OF MODEL PREDICTIVE CONTROL APPLIED TO THE FRENCH DEMO OF INTERFLEX

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ABSTRACT

In the course of the 2020 Horizon project InterFlex, French distribution system operator (DSO) ENEDIS is building Nice Smart Valley, a demonstrator to test innovative solutions for distribution systems. In their first use case, the network of the Lérins' islands is equipped with a variety of distributed energy resources (DERs) to investigate the combination of local storage systems and renewable generation, with specific focus on the temporary operation as a fully autonomous island. This paper presents the application of a previously developed model predictive control (MPC) based energy management system (EMS) to the demonstrator network under construction. Simulations show how the DERs can be used for different objectives like collective self-consumption and maximization of potential islanding time (PIT).

INTRODUCTION

Smart grids, microgrids (MGs) and local energy systems are all manifestations of the trend towards the decentralization of the hierarchical control architecture of the existing electricity grid. MGs usually encompass a section of the low or medium voltage (MV) distribution system, often connected to the remaining network only via a single point of common coupling (PPC), and can temporarily be operated as an independent island [1]. MGs allow to aggregate distributed energy resources (DERs) on a local level, optimizing their operation and increase reliability for specific sections of the grid.

The French distribution system operator (DSO) ENEDIS has taken active part in the development of MG solutions and demonstrations sites for several years. In the former Nice Grid project, the ability to combine DERs in the form of photovoltaics (PV) generation and battery energy storage systems (BESSs) to achieve islanded operation for a commercial district was demonstrated [2]. Building up on this experience they partake in the Horizon 2020 *Interflex* project, setting up a new MG demonstration site on the Lérins's Islands, close the coast of Cannes [3].

To facilitate the optimal utilization of MG resources, model predictive control (MPC) based energy management system (EMS) solutions were developed [4] and tested for generic networks [5,6]. The ability to switch to islanding operation was specifically taken into account, by maximizing the potential islanding time (PIT), i.e. optimizing the time that a MG can operate autonomously if an islanding command was received in the future [5]. The trade-off with other operational objectives was further demonstrated [6].

The application of an MPC based EMS was previously shown for the Swedish InterFlex test site [7]. This paper now applies a further developed EMS to the *Lérins's Islands'* MG to assess the versatility of the installed system. A simulation model is built for the MV section and 72 h of operation are investigated. In the MPC, multi-objective optimization is performed including the main operational aims decided for the demonstrator: Maximizing islanding capabilities and maximizing the self-consumption on the island of Saint-Honorat. Note that this study is based on the real assets of the French demonstrator but their control systems are simulated and do not exactly comply with what will be performed on the field.

MICROGRID DEMONSTRATION SITE

The French demo site includes part of the electrical infrastructure in and near the city of Nice, which already has a history as a test location for future aspects of distribution grid operation [2]. During the InterFlex project, six innovation streams are further investigated. Those are grid automation in combination with islanding capabilities, electric vehicle and energy storage integration, cross energy carrier synergies for more flexibility and demand response. Three use cases were formulated for the research [8]:

1. Islanding of a portion of the distribution grid using local resources;
2. Multiservice approach for grid-connected storage systems;
3. Local flexibility system operated by and for the DSO.

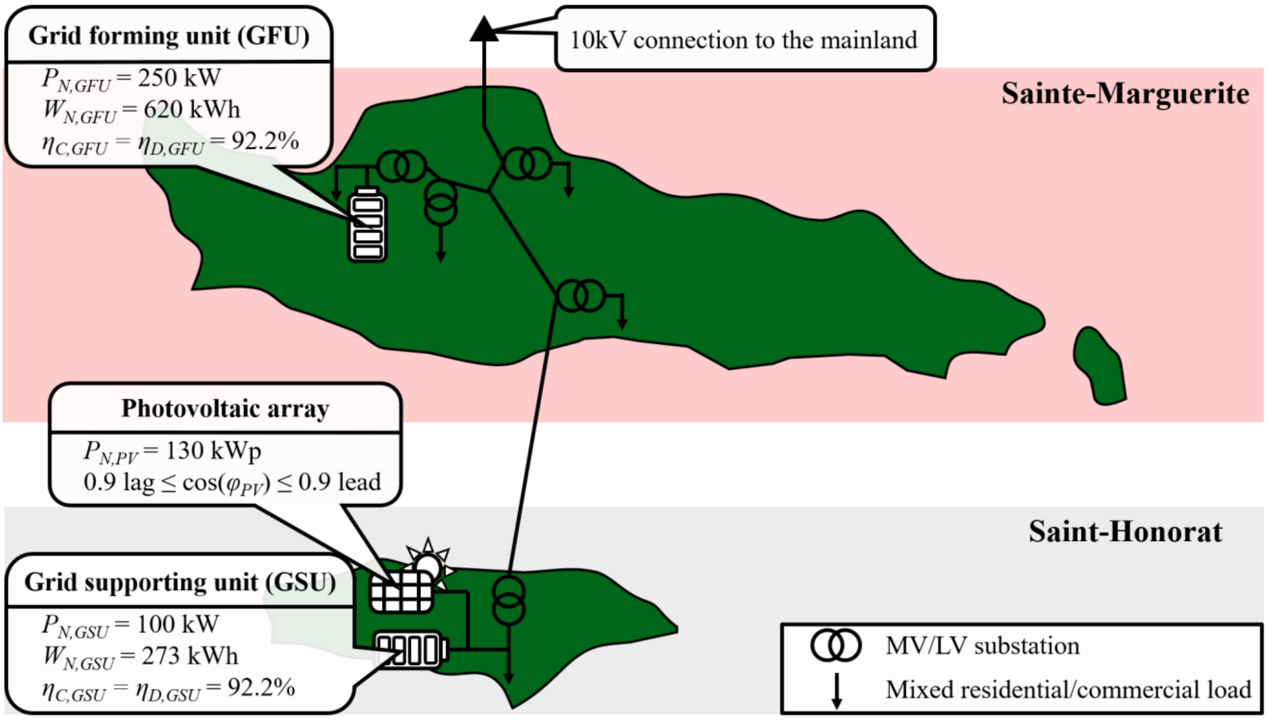

Fig. 1 Depiction of the Lérins' Islands, the MV grid section and the relevant DER.

The Lérins' Islands, located about 1.1 km from the shore of Cannes in southern France, were confirmed as the location for use case 1 in early 2018 as an area that may potentially see great benefit from the ability to temporarily switch to islanded operation. The islands are only connected to the remaining system via a single submarine cable of 10 kV of nominal voltage, i.e. there is no way to achieve topological N-1 reliability in case of a loss of this cable. Without a local backup supply, any planned or unplanned outage of the cable would lead to a full blackout of the islands' power grid.

Only the two largest of the Lérins' Islands are inhabited:

- Sainte-Marguerite, with a total land area of about 2.1 km² and four secondary substations;
- Saint-Honorat, with a total land area of about 0.37 km² and only a single secondary substation.

The total system load shows an annual peak of about 400 kW and is constituted by residential housing and commercial customers, the latter including restaurants, a museum and a monastery.

To allow temporary energetic autonomy, the islands' power system is extended with a combination of renewable generation and flexible energy storage:

- A BESS with a nominal capacity of $W_{N,GFU} = 620\,\text{kWh}$ and a nominal power of $P_{N,GFU} = 250\,\text{kW}$ was installed on Sainte-Marguerite, which will serve as the grid forming unit (GFU) in case of islanded operation.
- A BESS with a nominal capacity of $W_N = 273\,\text{kWh}$ and a nominal power of $P_{N,GSU} = 100\,\text{kW}$ should be installed on Saint-Honorat, which will not partake in the main balancing action and only work as a grid supporting unit (GSU).
- A PV array with a nominal power of $P_{N,PV} = 130\,\text{kWp}$ will probably be installed next to the GSU on Saint-Honorat and is considered in this analysis.

The MV grid of the islands' grid as well as the DER are illustrated in Fig. 1. The installed system aims to use the GFU to allow islanded operation for the system as well as maximizing the self-consumption at the Saint-Honorat substation by utilizing the PV array and the GSU. Note that the assets of NSV were not designed to perform long-term islanding. They are installed to test islanding without interruption on MV-grid that Enedis will be able to remotely start from its control room.

CONTROL SYSTEM

Microgrid control is commonly implemented as a hierarchical system of three levels distinguished by their response time:

- Primary control implements immediate local responses to voltage and frequency variations in the network on a second or sub second timeframe.
- Secondary control constitutes set point readjustments to account for steady state deviations of voltage and frequency on a timeframe of several seconds to minutes.

- Energy management pertains the optimal scheduling of resources to achieve best collective use of available flexibility in all DER. The time frame ranges from multiple minutes to hours.

A comprehensive overview of microgrid control with a focus on the EMS is found in [9]. This work does not implement lower level equipment control, but instead focuses on the EMS to allow general statements about the response to the system operator's overall objectives.

Model Predictive Control

Similar to the studies conducted and proposed for the Swedish demonstration site [7] this study uses a central MPC based EMS, which was extensively tested for a generic distribution grid [5,6]. MPC, also referred to as receding horizon control, was originally developed for the optimal control of slow moving chemical processes, but has recently found much success in EMS applications in recent years.

MPC uses repeated optimization to determine the optimal control set points for all assets. It leverages concurrent measurements and forecasts about future system inputs starting at current time step *t* as well as a dynamic model to predict the systems response. Optimization of control actions is performed for a set of timesteps $t \in \{1, t+1, \dots, T\}$ of fixed length Δt. Here, inputs refer to forecasts of consumption and PV generation. Control can be actuated as set points for DERs' active and reactive power. Of the resulting control actions, only the first is implemented for each DER. The horizon is then shifted to the next timestep and optimization is performed again based on updated measurements and forecasts. Advantages of MPC include the possibility to base immediate control on future system behavior, the inherent robustness of optimization with updated measurements and the explicit consideration of system constraints.

Optimization problem

The optimization is formulated as a mixed integer second order cone problem, that includes:

- a full set of optimal power flow constraints for radial power grids;
- the explicit formulation of the connection status to the main grid in the integer variable $\delta_{PCC}(t)$
- various device constraints for the BESSs and PV array, based on their technical specifications.

The detailed modeling is found in [5, 6].

Objective

Optimization refers to the minimization of a predefined operational objective formulated in mathematical form. Analogue to [6] the EMS employs a weighted linear combination J of four separate objectives:

$$J = \frac{\rho_{PIT}}{k_{PIT}} J_{PIT} + \frac{\rho_P}{k_P} J_P + \frac{\rho_{PEAK}}{k_{PEAK}} J_{PEAK} + \frac{\rho_{loss}}{k_{loss}} J_{loss} \qquad (1)$$

ρ and k respectively refer to the objective weight and a normalizing constant that aims to maps the objective to the range of [0,1]. In detail:

- J_{PIT} is the number of time steps that the MG is connected to the main grid starting in the next hour (t=t+1). Minimizing J_{PIT} corresponds to maximizing the PIT.
- J_P is the net energy exchange at the substation of Saint-Honorat. Its minimization i.e. leads to a maximum use of local energy (PV generation).
- J_{PEAK} is the summed square of the power exchange with the main grid. Its minimization i.e. leads to a peak shaving characteristic.
- J_{loss} are the total energy losses incurred in the regarded time horizon.

J_{PIT} and J_P map the original project purposes to the MPC controller and are therefore weighted relatively higher. J_{PEAK} and J_{loss} refer to auxiliary objectives that are included to utilize BESS flexibility if no improvement can be achieved for the former objectives. They further serve to improve convergence of the optimization.

SIMULATION SETUP

The simulation was implemented in MATLAB Simulink [10] and combines the YALMIP toolbox [11] with the GUROBI solver software [12] for optimization. The controller time constant is set to $\Delta t = 1$ h, using a forecast horizon of $T = 24$ h.

System parameters

Grid impedances were calculated from the cable data provided by Enedis. The cyclic efficiency of the BESSs was assumed as 0.85. This results in charging efficiencies $\eta_{C,GFU} = \eta_{C,GSU} = 0.922$ and discharging efficiencies $\eta_{D,GFU} = \eta_{D,GSU} = 0.922$, attributing losses equally to both operational modes. Apparent power limits of inverters were assumed to align with the nominal active power limits of the respective BESSs and PV array. Additionally, limited power angle controllability was assumed for the PV array within the limited range of $0.9\ lag \leq \cos(\varphi_{PV}) \leq 0.9\ lead$. The GFU is initialized with a state of charge (SOC) of 1 to reflect its purpose of withholding resources for islanded operation. The GSU is initialized with an SOC of 0.5, allowing equal upward and downward flexibility for improving self-consumption at Saint-Honorat.

Time series

As measured load or generation data were not available at the time of this study, synthetic profiles were generated. Load profiles were generated in a weighted linear combination of the normalized German standard load profiles [13] for residential customers H0 (weighted by 0.25) and general commercial loads (weighted by 0.75). The weights approximate the nominal composite of residential and commercial in the network. The load was then rescaled to reflect the maximum consumption of

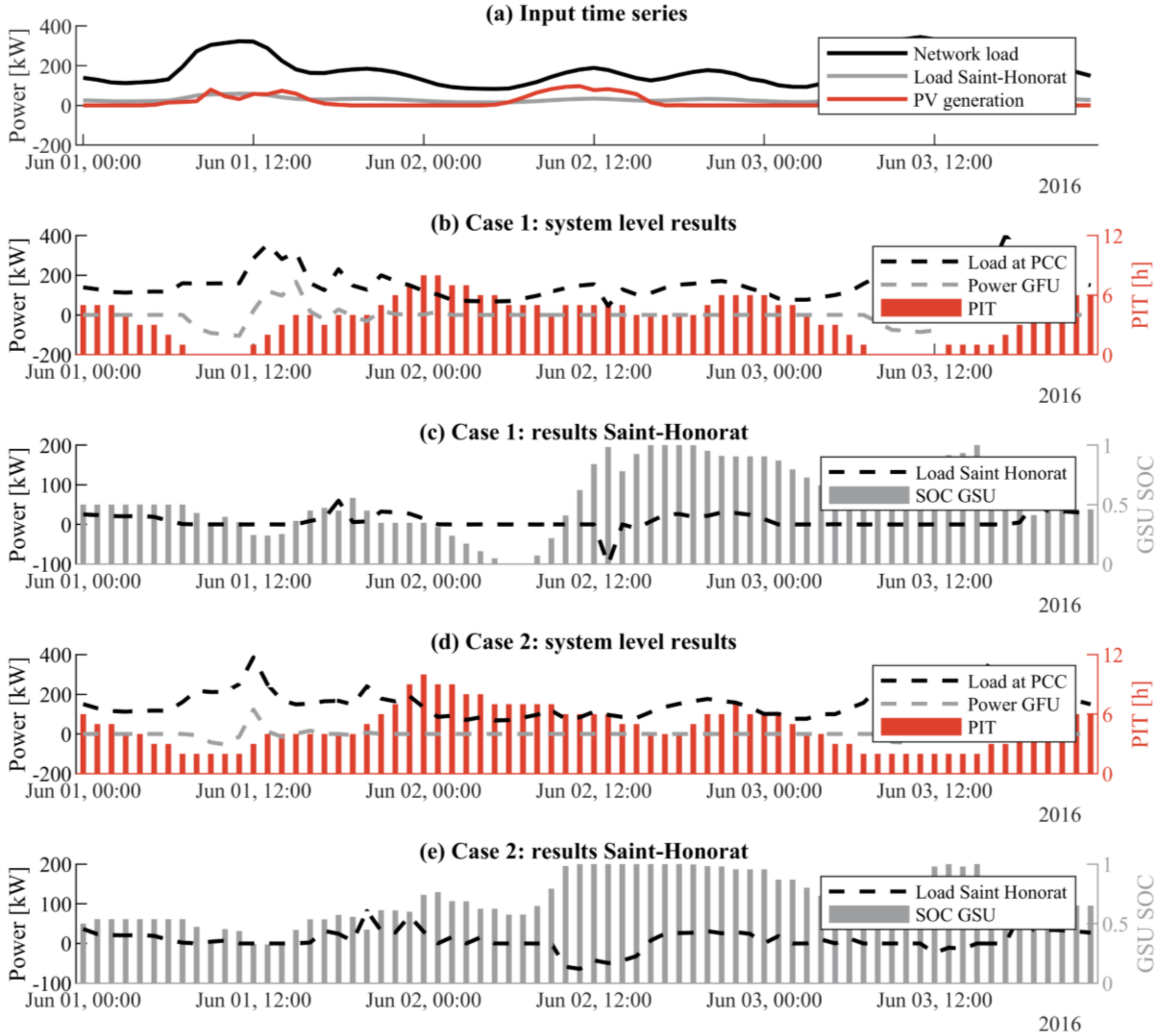

Fig. 1 Input data and simulation results: (a) 72 h input time series of network load, PV generation and load at Saint-Honorat; (b) Time series of optimized load at the PCC and GSU, as well as PIT in case 1; (c) Optimized load time series of load at Saint-Honorat and SOC of GSU in case 1; (d) Time series of optimized load at the PCC and GSU, as well as PIT in case 2; (e) Optimized load time series of load at Saint-Honorat and SOC of GSU in case 2

400 kW and distributed to the individual substations in proportion to their contribution to the islands' total load.
A PV profile was generated using the European Commission's PVGIS tool [14], assuming alignment of azimuth and slope are optimized for maximum annual energy output. A representative period from the 1st to 3rd June 2016 was chosen to simulate 72 hours of operation with high PV generation. Time series are shown in Fig. 2 (a). Perfect forecasting was assumed for all time series, as the aim of this study were potential benefits of the MG installation rather than operation under uncertainty.

RESULTS

Two cases were simulated to contrast different operational strategies:

- Case 1 emphasizes both the maximization of the PIT as well as the local resource usage at the island of Saint-Honorat.
- Case 2 emphasizes only the PIT maximization and serves as demonstration to islanding possibilities if both BESSs were mainly used for autonomy optimization.

The weighting factors for the objective are listed in Tab. 1. A weight of 5 (compared to 1 otherwise) was chosen to emphasize objectives, which works well in practice.

Table 1 Objective weights for both simulation scenarios

	ρ_{PIT}	ρ_{P}	ρ_{PEAK}	ρ_{loss}
Case 1	5	5	1	1
Case 2	5	1	1	1

Fig. 2 encapsulate the simulation results in the original 1 h resolution. For case 1, Fig. 2 (b) shows the active power at both the PCC and the GFU on the left axis and the resulting PIT on the right axis. Fig. 2 (c) displays the resulting load at Saint-Honorat on the left axis and the progression of the GFU's SOC on the right axis in case 1. Fig. 2 (d) and (e) provide the same data for case 2.

A comparison of Fig. 2 (b) and (d) shows that the system can fail to provide sufficient resources for islanding during peak demand hours just before noon, if the GSU is mainly used to maximize self-consumption at Saint-Honorat. In case 1 the GFU would then temporarily operate to lower the overall system load, until islanding becomes possible again. It is then recharged rapidly. In comparison islanding is always possible in case 2, with both BESSs kept at a relatively high SOC in preparation. The average PIT becomes 3.71 h with a maximum of 8 h in case 1. In case 2 an average of 4.71 h with a maximum of 10 h is achieved.

Generation never exceeds the system load and only 14.22 % of the energy consumed by the whole system are produced by the PV array. It theoretically covers however about 78.08 % of the energy consumed at Saint-Honorat for the simulated period, of which however only 49.74 % would be covered without any BESS. The remaining energy would be exported to the rest of the grid. In comparison, 69.66 % of the energy were covered by the combination of PV array and BESS in case 1, which decreases to 59.22 % in case 2, when the GSU is also used provide reserves for a potential islanding event.

CONCLUSION

In this paper, a central MPC based EMS was successfully applied in a simulation of the MG demonstration site of the Lérins' Islands. Two scenarios were compared assuming different operational objectives. They reveal some of opportunities that arise from an optimal scheduling of DERs. It should be noted that results are based on hypotheses about load and generation profiles as well as perfect forecasting. Results can therefore only provide limited propositions for real world operation.

According to the hypotheses, it was found that for an operational strategy that puts emphasis only on the maximization of PIT and withholds resources accordingly, the MG would be able to switch to islanding mode for at least 2 h at any time in the given simulation. If equal focus is however put on the local self-consumption at the Saint-Honorat, islanding becomes impossible during some of the daily peak hours. In return local self-sufficiency increased by nearly 10 %.

Future work will incorporate real world experiences of operating the islands' MG system. Measured load series can be used to achieve results that better map true consumer behavior and the effect of uncertainty in the MPC in combination with the adjustments done by lower control level will be investigated.

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