A Tool that Uses Demand Side Management for Planning the Grid Response to Outages

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Abstract. This work addresses the electric grid planning process in general and the outage response in particular. Using the advance control architecture of microgrids, we show that by planning for demand reduction in the microgrids, certain outages can be mitigated, without the need of additional local generation or islanding. We describe the load models, their outage behavior and present the results in a case study.

Keywords: Grid planning · Grid outage response · Energy flexibility · Demand management · Microgrid control · CEMS controller

1 Introduction

The reliability of power supply is increasingly threatened both by natural disasters like floods, storms, earthquake, and by cyber attacks on the power grid.

The energy system stakeholders, such as city planners, facing budget constraints, need to decide which parts of the grid are (a) most vulnerable to various attacks and natural disasters and (b) most critical from a societal, economical, or functional point of view. In order to analyse the response to an outage they first need a simulation environment in which different buildings can be plugged in as electrical loads, generators, storage, etc. One first step in this direction is presented in the work conducted in the JPI Urban Europe project IRENE[1].

IRENE has developed a methodology for the city planners and other stakeholders to address systematically the threats on the grid operation and to find ways to prevent a part of them (especially the cyber attacks). In case an outage is inevitable, as in the case of a natural disaster, one way would be to provide power supply backup for certain islands, another approach would supply only the critical demand, or a combination of the two. In Fig. 1 the general planning process and the tools developed in IRENE are mentioned.

In this work we propose a demand reduction approach in order to deal with a certain type of outages due to power interruption. This planning approach is supported by the Microgrid Evaluation Tool (MGE) that is described in the following by means of a use case study and simulation results.

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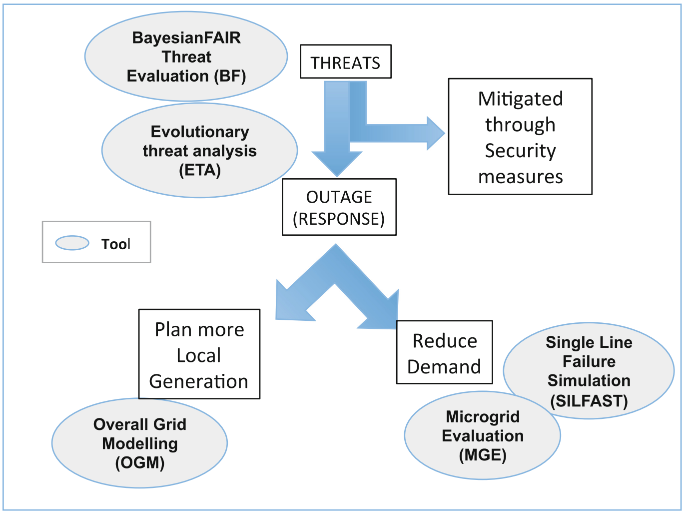


Fig. 1. IRENE planning process and tool overview

2 Types of Outage and Outage Response

A number of previous works describe the anatomy of power outages in the grid, stressing the cascading effect of outages leading to blackouts [11,12]. A well-known method is to simulate single-line contingencies, i.e. the outage of one of transmissions or main distribution power lines.

Not all the outages manifest themselves by transmission line interruption; power plants, substations and SCADA systems may also be damaged or attacked. At the edges of the grid, so called Microgrids [1] have the capability to disconnect from the main grid (islanding). Planning a microgrid against total loss of power includes adding dispatchable local generation. Once the outage is detected, the microgrid goes in islanding mode and the generators ramp up their power. A detailed grid resilience study in the New York state [9] estimated that the costs of migration to a microgrid with islanding capability, including backup generators (during an outage) become higher than the benefits. However, conclude the authors, if the microgrid participates in demand response program, such that the peak demand is reduced, then less generation capacity is needed and the microgrid solution becomes economically feasible.

Several threats including natural disasters like floods, storms, earthquake, and cyber attacks, frequently result in the disconnection of a power line. This leads to a drop in the supply, not necessarily to a total loss of power. The single power line failure simulation is a known method to check the resilience of a grid. Following a link removal from the grid topology, the single line failure simulation tool (SILFAST) recalculates the power flows and provides information about the node voltages and line currents. Lines that exceed the nominal current (are overloaded) would trigger the circuit protection after some time and trip (disconnect), causing other lines to be overloaded and so on. This cascading effect observed during the emerging of a blackout could be avoided through immediate reduction of the demand in each of the grid nodes.

The use case discussed in the rest of the paper begins therefore with an outage caused by a partial drop in the supply capacity, as simulated with the developed SILFAST tool. Each node of the grid, organized as a microgrid, receives the outage alert and is able to reduce its demand. The simulation on microgrid level determines the new reduced demands. By repeating the simulation of different outages with the reduced demands, we can determine the nodes where local backup generation has to be added.

3 System Overview

We make the assumption that the studied smart grid consists of microgrids at its edge - local grids with loads between a few hundred kW and several MW. The microgrid architecture has been proposed in previous research due to its advanced control mechanisms for local generators (DER), to its flexibility, reliability and islanding capability [1,3,5].

Few works have studied, however, the impact of Demand Side Management on the microgrid operation during long lasting outages. Using the classification in [3] we adopted a secondary control centralized architecture, in which the time horizon is in the range of a few hours, that is, significantly larger than for primary control systems.

The control system in Fig. 2 covers only the microgrid level and consists of the microgrid (MG) controller and a number of customer energy management controllers (CEMS) associated to each of the buildings in the microgrid.

In the current approach controllers use flexibility information, demand management and scheduling to cope with the changes in the power supply caused by an outage [4]. The flexibility concept applies to those loads which are tolerant (in certain limits) to an increase, decrease or shift in time, such as a thermostat controlled cooling, a battery charging, etc. The idea is to let other systems, energy providers, aggregators know (and pay for) this information. Demand Side Management (DSM) includes mechanisms based on flexibility, price information, or direct load control, that allow external actors to modify the demand of a consumer.

For the realisation of the control loop, the Model Predictive Control (MPC) technique [2,6] is used, meaning that the power consumption (and generation) is predicted for a certain time horizon (e.g. six hours), however the actuation is performed only for the next period. The MPC mechanism is combined with the periodical exchange of flexibility information between controllers, see Fig. 2. Energy flexibility models exist in this system for HVAC (heating, ventilation, air conditioning), electric vehicle charging and battery storage. Each CEMS controller aggregates the flexibility of its assets and reports the resulted profile (during the time horizon) together with the planned consumption profile. The latter is the result of an optimization step, taking into consideration local goals,

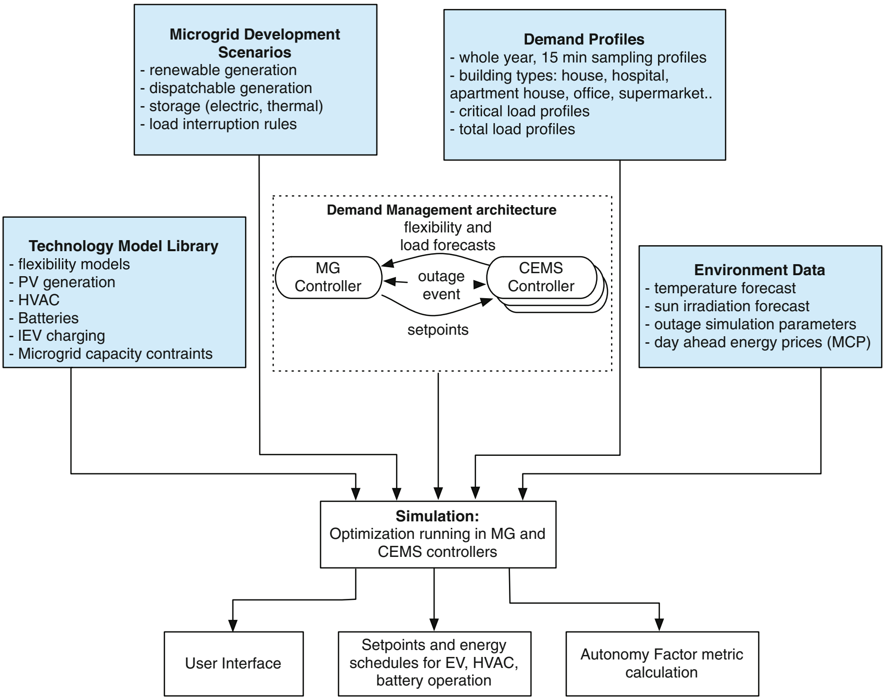


Fig. 2. Microgrid planning system overview

the desired load value from the MG controller perspective (called setpoint) and constraints from local assets.

The MG controller reads the latest flexibility and consumption plans from the CEMS and computes updated setpoints (for the whole time horizon). In case the CEMS proposed consumption is too high, the setpoint following objective in the CEMS optimization has the effect that some flexible loads are reduced (within their flexibility limits). For details, see [10].

3.1 Power and Energy Flexibility

Demand Side Management can be performed either through direct load control or through price signals. Direct load control needs however more information about each load flexibility, besides historical load profiles. For energy storage devices such as EV charging, home batteries, profile data is anyway not available. Therefore, we have developed models that predict the consumption and calculate the flexibility information. Power flexibility (minimum and maximum power in each time period) and energy flexibility (minimum and maximum) models are provided for the following appliance types: (see [7,10]).

- HVAC
- EV charging
- (home) battery

In Fig. 3 the EMS controller receives information from the models and static load profiles. As a result, various control variables for the local flexible loads are updated, and new values for PV generation, consumption and flexibility are estimated.

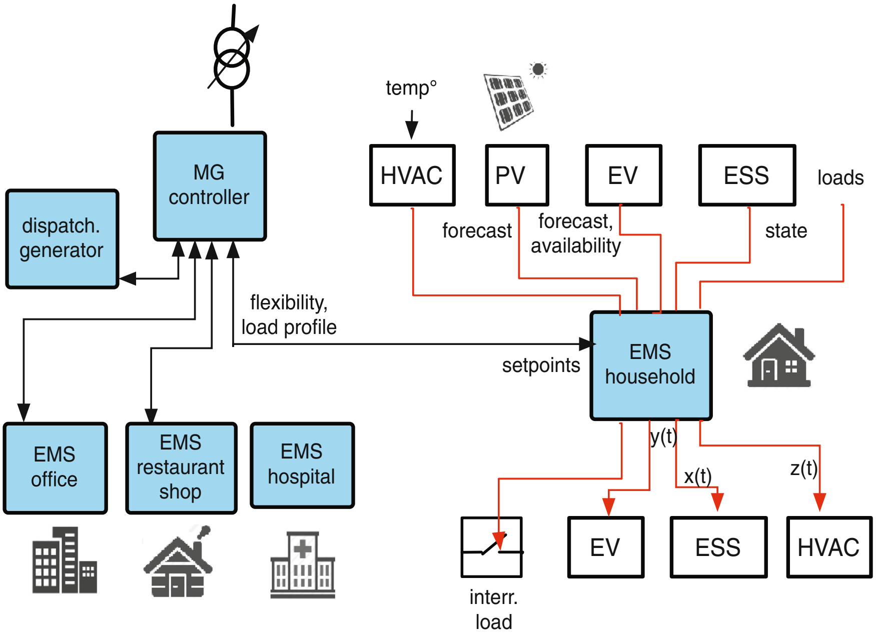


Fig. 3. Building model with its inputs and outputs

3.2 Demand Characterization

For the purpose of planning the consumption of a microgrid, both in normal operation and in outage mode, load profiles are the main source of information.

The EIA (Energy Information Administration) provides high qualitative annual consumption data on a hourly basis, for various climatic regions in the US. The Chicago area has been selected, as it seems to be the most similar to northern Europe.

Fortunately, the consumption data of residential and commercial buildings in [8] has been de-aggregated in the categories ventilation, cooling, heating, lights and equipment. To these categories we added model-based loads such as EV charging, home battery storage, as well as PV generation. The cooling/heating consumption has been modeled separately in order to exploit the flexibility due to heat storage. We used a simplified thermodynamic model of the building and thermostat based control. The HVAC models have been then calibrated to match the yearly consumption in the profiles.

The critical demand has to be defined for each building type in advance, and consists of loads and appliances that have to operate during an outage. The rest is interruptible load and will be discontinued during the outage. Here are some example (not all the appliances below have been modeled).

- partial lighting in houses, commercial places, industrial
- local controllers (e.g. CEMS), microgrid controller
- wireline communications (ICT infrastructure for control, internet) and WLAN, cellular nodes and antennas,
- cash dispensers and their communication infrastructure
- refrigerators in food stores, pharmacies, hospitals, storage houses.
- water pumps for district/town
- gasoline pumps in gas stations
- lifts and automatic doors in house blocks and commercial
- special buildings: hospital, pharmacy, police and fire stations
- gas-based space and water heating (needs electronics to operate).

Interruptible loads are by definition disconnected during an outage. Examples of interruptible loads in the household are: loads in the kitchen, entertainment, washing machine, vacuum cleaner, air conditioning, EV charging. In the EIA dataset and also throughout Europe, (depending on building type and climate region), space and water heating is often done with natural gas. Therefore, the visible electricity consumption during the summer due to air conditioning is higher than in winter.

In Fig. 4 the obtained critical consumption and the total consumption are depicted for a house and a small office. In case of the house P_{in} is the total consumption, obtained by adding to the critical load (fan, light and equipment) the HVAC, EV charging and PV generation: $P_{in} = P_{critical} + P_{HVAC} + P_{EV} + P_{PV}$.

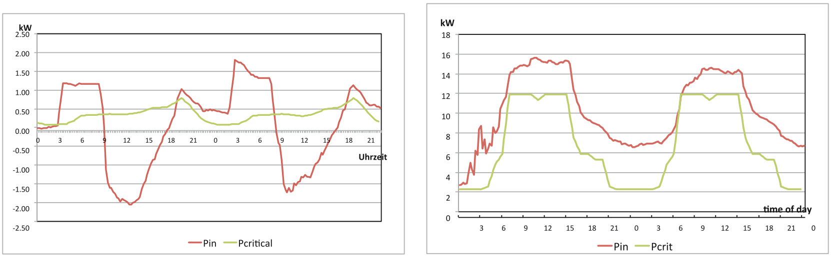


Fig. 4. Consumption profile examples: residential house (left), and small office (right)

Table 1. Summary of building characteristics

Building type	Size [sqm]	Critical: fan (f), ICT (i), light (l)	Interruptible:	PV kWp
Residential flats	3100	f, i, l	HVAC, EV	
Small office	511	f, i, l	HVAC	8
Residential house	250	f, i, l, battery	HVAC, EV	5
Supermarket	4180	refrig., f, i, j		
Clinic	3804	f, i, l, HVAC		
Battery 100 kWh		x		

4 Microgrid Evaluation Tool Operating Modes

The MGE Tool is an event based simulation of the interacting CEMS controllers and the MG controller. Each HVAC, EV, and battery load model in a building produces at each iteration an updated load prediction and flexibility information which is combined with the "static" load profile. The CEMS optimization updates the local control actions. On the MG controller side, the optimization of the load "distribution" consists of the setpoint update for each building controller.

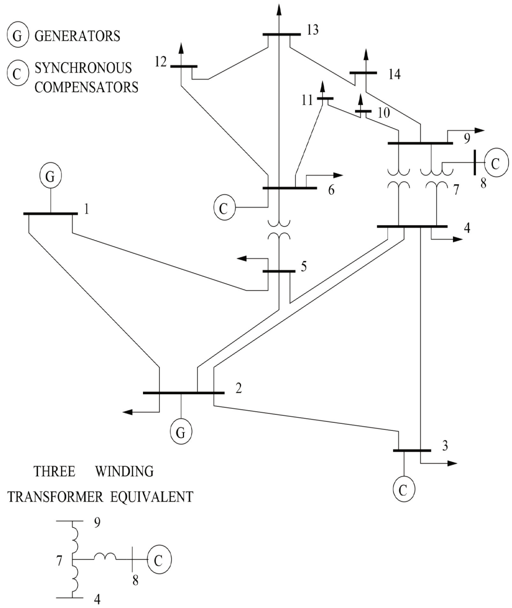
Once an outage event is received by the controllers in the microgrid, each CEMS controller activates certain rules concerning the critical/interruptible load classification. The rules can be restrictive or more relaxed, depending on the energy balance, i.e. the amount of dispatchable generation available and the societal needs in the different building types. In Table 1 columns 3 and 4 indicate the load types defined as critical and as interruptible.

- economic, price dependent criteria are disabled in the CEMS optimization, the load profiles still must follow the setpoints and keep the strict balance between supply and demand, as mentioned in [1].
- shedding the PV generation is not allowed, the PV output is maximized.
- interruptible loads are disconnected.
- the air conditioning/heating may be switched off in certain buildings to save energy. In any case thermostat limits are relaxed to increase flexibility.
- EV charging is either disabled or may use only local renewable energy.

The result of the simulation is the detailed load profile of each of the components before, during and after the outage. Generation (renewable) and battery storage are considered as well. Finally, the total load profile of the microgrid is computed during a particular outage situation, outage duration, time and date of occurence.

5 Case Study

In this section we use a benchmark grid, the IEEE 14-node test topology in Fig. 5. The original capacity of 280 MW has been scaled down, and each of the



Node	Type	Pgen	Qgen	P_{LOAD}	$P_{REDUCED}$
1	3	2.32	0.0	0.00	0.000
2	2	0.40	0.0	0.217	**0.160**
3	2	0.00	0.0	0.942	**0.550**
4	0	0.00	0.0	0.478	**0.250**
5	0	0.00	0.0	0.076	0.076
6	2	0.00	0.0	0.112	0.112
7	0	0.00	0.0	0.00	0.000
8	2	0.00	0.0	0.00	0.000
9	0	0.00	0.00	0.295	**0.200**
10	0	0.00	0.00	0.090	0.090
11	0	0.00	0.00	0.035	0.035
12	0	0.00	0.00	0.061	0.061
13	0	0.00	0.00	0.135	0.135
14	0	0.00	0.00	0.149	0.149

Fig. 5. Left: Selected overall grid topology. Right: Loads in the adapted 14-Node test grid

Failed line	Overloaded lines (regular bus loads) current [kA]	Overloaded lines (at reduced load)
No failure	1-2:3.5	
1-2	1-5: 5.6, 4-5: 2.8, 5-6: 2.1	1-5: 3.5
1-5	1-2:5.4	
2-3	1-5:2.2, 3-4:2.4, 5-6:2.1	
2-4	1-5:2.2, 2-3:2.1	
2-5	1-5:2.2	
3-4	2-3:2.3	
4-5	5-6:2.2	
4-7		
4-9	5-6:2.4	5-6: 2.26
5-6	4-5:2.4	
6-11		
6-12		
6-13		
7-8		
7-9		
9-10		
9-14		
10-11		
12-13		
13-14		

Fig. 6. Results of SILFAST - the contingency test

nodes can be populated with a microgrid, such that the loads correspond to P_{load} values in Fig. 5.

As mentioned in Sect. 2, running the single line failure tool (SILFAST) is used to perform contingency tests [13]. It simulates a grid capacity reduction, because the load remains the same but the capacity is reduced due to outage of

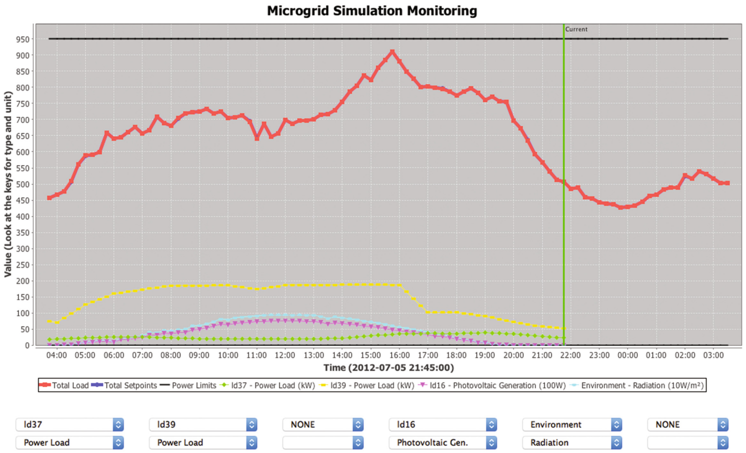


Fig. 7. Node3, Microgrid net consumption, normal simulation

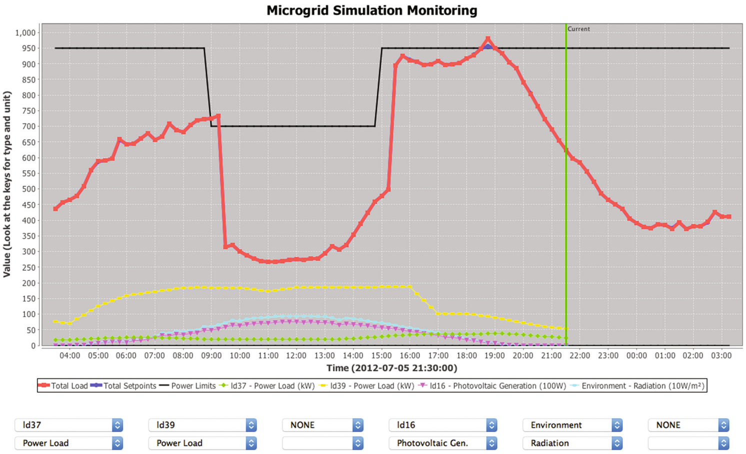


Fig. 8. Node3, Microgrid net consumption, outage simulation (6 h)

one distribution line. As a result, several other lines are overloaded as we can see in column two of Fig. 6.

It is assumed that the microgrids, which consist in our case of a set of buildings, are associated to the respective nodes. In Fig. 5 the total nominal load of the nodes is shown. For the demand reduction we selected the largest nodes 2, 3, 4 and 9. The other nodes do not reduce their load during an outage.

The MGE Tool is being used to determine the reduced load. Figure 7 shows the total load of Node 3 in normal operation mode and in case of an outage between 9 am to 3 pm, see Fig. 8. The user interface allows to select single CEMS or components (EV, PV generation, battery) to be displayed during the run. On the right of actual simulation time, the predicted load values are updated each iteration, and corrected so that they do not exceed the setpoint values.

With the obtained reduced load values, the single line failure simulation is run again. The results can be seen in of Fig. 6. In the 3rd column, most overload situations disappeared, only two overloaded lines 1–5 and 5–6 remain, a situation which could be improved for example by adding local generation at node 5.

6 Concluding Remarks and Further Work

In this work we addressed the outage response of a microgrid entity, from an energy management perspective. The approach is generic: it provides a framework for configuring different type of consumer (buildings) with a number of flexible loads: thermal and electric storage, renewable generation, in addition to a precise classification of interruptible and critical loads in every building.

The developed simulation tool makes use of course of a particular demand side management algorithm (described in detail in [10]), which could however be replaced with another one.

The simulation result depends heavily on the consumption profiles and the distinction between critical and interruptible consumption that has to be made for each scenario. To the critical loads we count ICT systems which include the controller, the internet connection and various wireline and wireless communication systems. Although entertainment equipment is not necessarily critical, a functioning internet radio and TV are crucial in emergency situations. Additional outage rules can been configured in the model, in case for instance air conditioning or EV charging should be enabled during an outage.

Dispatchable generation can be planned complementarily or in combination with DSM. More case studies have to be made in order to determine the feasibility and costs of DSM in comparison with backup generation.

Using Demand Side Management together with rules for critical load identification for planning an outage response is helpful only if such a scheme can work similarly in practice and if it is economically viable. The CEMS and MG controllers are real software components working on historical profile data. The problem in a real setting is the delay between the outage event and the load reduction, see Fig. 8. Currently, this delay is due to the sampling time (15 min) and needs to be reduced substantially in a practical realisation of the proposed scheme.

Concerning the implementation costs, DSM comes with a higher costs both for planning and for the operation of control and communication systems in the microgrids. Moreover, in order to control the critical and the interruptible loads, changes in the electric wiring in each building have to be performed. However, alternative solutions could be much more expensive [9].

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