AGENT-BASED DISTRIBUTION GRID OPERATION BASED ON A TRAFFIC LIGHT CONCEPT

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ABSTRACT

Compared to a centralised grid operation management for the distribution grid, a distributed and decentralised agent-based operation has a lot of advantages, like scalability, modularity and robustness. We propose the concept for an agent-based distribution grid operation management based on a traffic light concept. Depending on the situation in the grid, the operation management can be in different modes, which define the way how the grid is operated.

INTRODUCTION

Caused by a rising concentration of interactive generators and consumers in the distribution grid, distribution system operators (DSOs) everywhere in Europe face new challenges for the management of their grids. However, this new situation also pushes for new possibilities for the operation of the grid [1]. In order to avoid classical grid reinforcement methods while at the same time increase the stability of the grid, the development of a smart distribution grid is necessary. This especially includes an active consumer and producer involvement. Due to the fluctuating nature especially of renewable energies, adaptive solutions must be found that can react to heterogeneous situations in different parts of the grid [1].

Agent-Based Grid Operation Management

Compared to a centralised grid operation management for the distribution grid, a distributed and decentralised agent-based operation has a lot of advantages [2], [3], [4]. Such a locally operating intelligence can naturally adjust to locally varying operation conditions. Depending on the situation in the grid, different actions can be taken in different parts of the grid to improve the overall system status. Furthermore, they can offer a certain technical redundancy and thereby an increased robustness [4].
In [5], [6] and [7] concepts and frameworks for agent-based self-healing power grids are described. These papers share the idea of several operating states in which the grid can be, depending on the condition of the grid.
We follow this idea of distinct operating states in our approach for the grid operation management and expand on it. The authors of [4] present several use-cases and functionalities for an agent based grid automation. Our approach provides partly the same functionalities, but extends the separate treatment of use-cases to a comprehensive view so that the system can not only handle different use cases and methods but can also decide by itself which strategy to pursue. In [8] the outlines and concepts for a comprehensive agent-based grid operation management system are proposed and the work in the here presented paper is part of that approach.
The grid operation management mentioned above [8] is build up as a layered but nevertheless flexible and dynamic structure of several so-called agents, i.e. locally operating software intelligences, with varying areas of influence and tasks in the grid, see Figure 1 for a schematic representation. As the DSO is responsible for the secure operation of the distribution grid, there are several so-called DSO agents, each of them overseeing a distinct topological area of the grid, a so called cell. Additionally, distributed generators and controllable loads, together called prosumers, are equipped with agents to participate in operation management. To ensure the unbundling of energy production and grid operation, these prosumers mainly interact with a commercial aggregator in order to sell their services. The latter aggregates several small-scale prosumers, integrates and represents them on the markets. Nevertheless, the DSO agents know about the prosumers and can interact with them directly if necessary (e.g. in state of emergencies, see below). Each DSO agent runs a grid operation management. This is supervising the grid in real time but can also anticipate the near future and schedule actions.

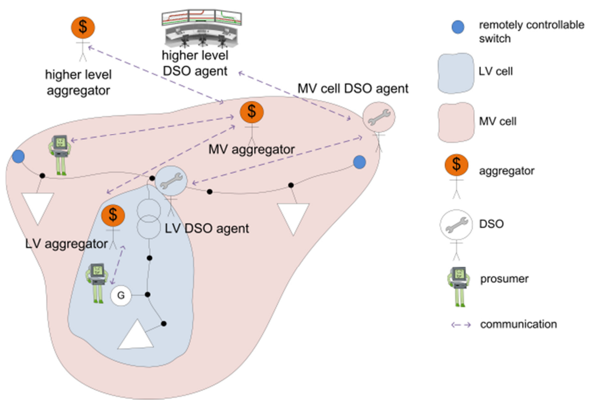

Figure 1 Schematic representation of the proposed agent structure

CONCEPT OF THE GRID OPERATION MANAGEMENT

The Operation Mode

The distribution grid operational management we developed is inspired by the power system traffic light idea proposed by the BDEW-roadmap [9]. Based on the system status of the grid, this traffic light describes the legal and regulatory interactions between the markets and the grid. The possible system states are thereby equivalent to the three phases of a normal traffic light: green (normal), amber (critical) and red (emergency). We translate this concept into a specific operation model for the grid operation management, see Figure 2.

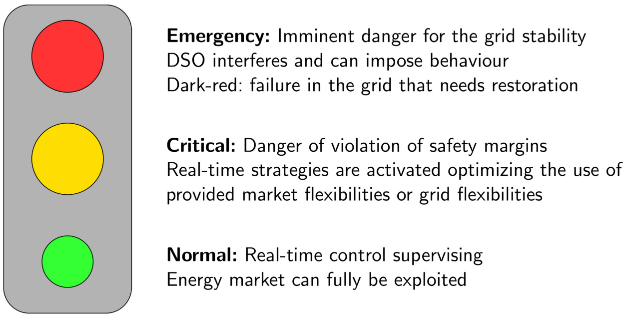

Figure 2 Operation modes of the grid operation management inspired by the power system traffic light system

In the green phase, the normal mode when operating the power system, no critical system states or threshold value violations are occurring. This phase defines a market dominated operation of the prosumers. The energy-contracts placed by them via the commercial aggregators for day-ahead or intra-day are valid without limitation. The real-time control of the DSO agent supervises and evaluates the system continuously.

At the other end of the power system traffic light, in the red phase, also called the emergency mode, the grid stability is in imminent danger. The strategies deployed in the red phase will result in fast, clear and mandatory signals from the DSO agents to the prosumers but also to other clients and generators in the affected cell.

A special phase is introduced by the so-called dark-red phase, in which an outage already occurred (mainly due to failures), and the affected parts of the grid need to be re-energized as fast as possible while resupplying as much load as possible by using the possibility of reconfiguration of the grid and flexibility use.

Between the green and red phase there exists a transition phase, similar to the amber phase in a traffic light. It describes the critical mode, where the compliance with quality criterions is possibly violated. The feasible actions that can be taken in this situation use the real-time flexibilities provided by the aggregator for the DSO cell agent but also flexibilities that arise from the grid itself, like capacitor banks, OLTC transformers or the grid configuration. In this phase, objectives can vary depending on the situation and the preferences of the DSO, the forced intervention of the DSO is not intended, and the flexibilities provided by the aggregators should suffice to achieve the desired objective.

It is important to notice that the operation mode can be diverse for different parts of the grid. Each cell can be optimized separately. Therefore, there will not be one power system traffic light for the entire grid but several ones to guide the operation at all important nodes in the grid, similar to the traffic lights on our roads. Consequently, this can lead to various strategies applied at the same time at different places in the grid and to different prices for real-time flexibility. Thus, flexibilities for the power grid can no longer be traded exclusively on European markets, but local markets should emerge from this distributed control concept.

The Interaction Mode

The diversity of locally applied strategies plus potential demands from upstream parts of the grid through the distributed multi-agent system bear the risk of leading to inconsistent and oscillating situations. This might happen, for example, when two DSO cell agents, situated at different feeders of the same substation and triggered by their local measurements, take counteracting actions. Such situations could lead to severe stability problems and oscillations. Thus, an important task of our grid operation management has to be the supervision of the interactions between the decision-making distributed agents. This includes also the possibility for the higher layer agent to interfere with the lower level agents if necessary. To realise this, a communication loop is defined that forces each agent to communicate its plans and status information to the next higher agent layer before putting them into practice, see Figure 3.

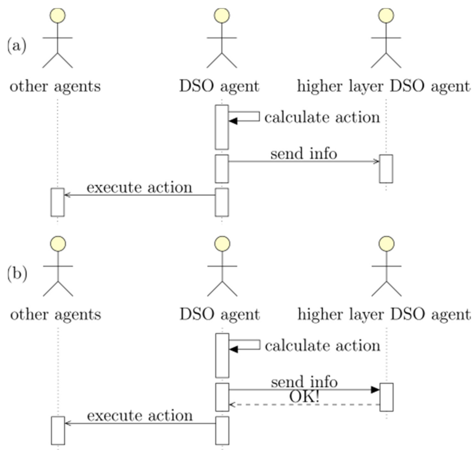

Figure 3 UML Sequence diagram for the communication loop with the higher layer DSO agent with mere information (a) or with forced waiting for approval (b)

While doing this, two modes are possible. The first, (a), requires just the sending of the status information without waiting the approval of the higher agent level, knowing that it has the possibility to interfere in case of interaction problems. The second one, (b), would require an explicit

approval from the higher level agent to authorise the execution of the actions.
In this context it is also important to define a clear hierarchy of command, which can lead to a consistent solution when conflicting instructions arise from different levels in the agent structure.

Level of DSO Control

The coordination of strategies according to the traffic light model will be done to optimize the advantages for the DSO. He guarantees the stability of the grid, the quality of service for his clients but also the security for the field crews working on the grid. Especially for the last case the DSO must be in the position to manually switch off parts of the automatic execution of the operation management for certain parts of the grid, while in other parts the system is still working by itself. Also it must be easily possible for the DSO to shut down the grid operation management completely. An intermediate step between a fully automated management system and the manual control is a so called semi-automatic mode, where the operation management still processes the grid situation but does not actually perform any action. Instead, it just proposes methods to the DSO, who can validate them (via the above proposed approval loop), modify them and/or can manually trigger their execution.

POWER SYSTEM TRAFFIC LIGHT SPECIFICATION

The power system traffic light is the key part of the main supervising and optimisation procedure of the DSO agents. It is a procedure that is executed in time steps of 10 minutes in nowadays configuration or on demand when a measurement unit reports significant deviations.
In preparation for the following time step t_n, during the actual time step t_{n-1} the prosumers announce their real time flexibilities for time step t_n to their aggregators. These offers of real-time flexibilities are always valid for exactly one time step, in which they can be used by the DSO agents. That means, flexibilities proposed by the prosumers in t_{n-1} will not necessarily be available in t_n, and the flexibilities used in t_{n-1} will no longer be influencing the grid in t_n.
Prior to time step t_n, at the very end of t_{n-1}, the DSO agent receives grid information from all the measurement points. This allows him to analyse his grid area and to compute his system. As the DSO agent knows which flexibilities were used in t_{n-1}, their influence can be subtracted in the state estimation. This provides an initial estimated grid state S_i at t_n, the state of the grid at upcoming t_n if the DSO were not to take any actions. This analysis just prior to t_n allows for a smoother transition between the time steps.
This resulting initial grid state S_i is analysed, especially concerning voltage profile violations at the buses of the grid and congestions on the grid lines.

For system limit violations, we define two thresholds: a critical limit L_1 and emergency limit L_2. The value of L_2 represents a threshold where a violation can lead to severe and imminent danger for the grid. The lower limit L_1 is used to trigger the start of the grid management intervention to avoid violation of L_2. L_1 can be chosen according to the preferences of the DSO, L_2 is assumed as a regulatory limit, as above this limit the DSO receives the right to suspend market mechanisms.
With beginning of time step t_n, the flexibilities that were used in t_{n-1}, end, and possible flexibilities of t_n are activated at the same time, based on the analysis and actions of the DSO agent. The resulting grid states at t_n may therefore be not equal to the initially computed ones as it is altered by the influence of the used flexibilities. For the rest of the paper this state is called the resulting grid state S_r. See Figure 4 for a timeline of the succeeding actions within the supervising and optimisation procedure of the DSO.

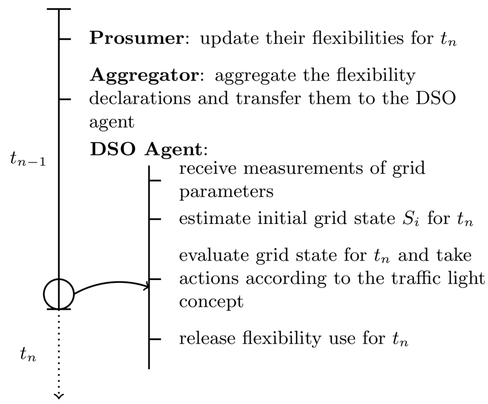

Figure 4 Timeline with actions to be taken within one time step

In the following, we will have a closer look on the phases and the specification of the traffic light.

Green Phase

The system stays in the green phase for as long as the analysis of the initial grid state does not show any violations of threshold L_1. Consequently, none of the real-time flexibilities proposed by the aggregators for the amber phase are employed by the DSO agent.

Amber Phase

As mentioned above, each time step starts with a state estimation of each cell. If at least one bus voltage or one line current of the initial grid state exceeds the limit L_1, this part of the grid transitions into the amber phase. All flexibilities provided by the aggregator as well as intrinsic grid flexibilities like capacitor banks, OLTC transformers and grid configuration are used as input to an optimisation algorithm in an attempt to improve the grid situation. Because of the high complexity, our proposed optimisation for this task is based upon a metaheuristic Particle Swarm Approach. Its objective/fitness function is of multidimensional nature and evaluates possible solutions. It does so according to the compliance of system limits, but it also aims to minimize the costs for the flexibilities that are used and the power losses of the system. For details on this multi-objective optimisation and its fitness function, please see [10]. The solution of this optimisation results in set points for the flexibilities provided by the prosumers, which go into effect at the beginning of the upcoming time step. Ideally, in the resulting grid state S_r all system parameters obey the limit L_1. Generally, S_r should always be better than the initially computed state S_i. It is important to note however, that respecting of L_1 after the optimisation does not change the grid phase back to green. The phase remains amber as flexibilities for the grid optimisation are used.

It can happen that in real grid operation none or only unsufficient flexibilities are proposed to the DSO agent within its cell. In this case we have the possibility to employ the distributed agent structure and the ability of the agents to dynamically interact. The affected cell, which lacks flexibility, can ask its neighbouring cells for the building of a so called federation of cells. That means that they dynamically join together to build a temporary unit. Natural leader of this unit is the cell that initiated the process. This cell then gathers the grid and flexibility information of the other participating cells and coordinates the optimisation (which could partly be parallelised). After the problem is solved, the federation is broken up again.

Another way to handle the lacking of flexibilities in one cell can be to pass the command from the local DSO agent to a higher level agent. This agent has a broader view on the system (including the neighbouring cells around the affected cell), other flexibilities at hand and can so try to find a solution.

Red Phase

The red phase is triggered when at least one bus voltage deviation or one line current violates the emergency limit L_2. In this phase, it is very important to find a new configuration that returns the grid back into a non-constrained and secure state as fast as possible, even if this is not necessarily the mathematically best possible solution. This is achieved with a simplified optimisation that is based upon the same method as above but stops execution as soon as a "sufficient" solution is found. In addition, the complexity of the fitness function is reduced, considering mainly the system state and violations of system thresholds. Another important difference to the amber phase is also that not only the flexibilities voluntarily provided by the prosumers are taken as input, but all clients in the grid. To avoid disturbances to critical consumers, like hospitals, etc. as much as possible, each client has a priority indicator assigned to it, which the optimisation takes into account.

In addition a further function becomes available in the red phase. It is the local reaction of the prosumers to locally detected problems. Each prosumer has a fall-back strategy implemented that describes its behaviour when it encounters a certain grid state at its connection points. This is very important as it guarantees certain behaviour in the case of communication problems and really severe situations that do not even leave any time to wait for the DSO signal.

Use of Integrator

As mentioned before, the main parameters for the definition of the traffic light phases are voltage profile violations and line loadings. Since extent as well as duration are important characteristics of violations, the "deviations" in each time step are integrated as long as the system stays in the amber or red phase. This is done for voltage and current separately. In the amber phase, if this integrator exceeds a certain limit, a federation of agents is build, which then tries to solve the problem within a wider context. This might allow finding a cheaper and more "optimal" solution for the problem.

In the red phase, a slightly different approach is chosen, and the control is passed to a higher agent layer. This approach loses the dynamic possibilities of the decentralised agents, but it is more secure in emergency grid situations.

Schematic Visualisation

In Figure 5 we visualise the behaviour of the grid operation management according the power system traffic light. For a single grid cell, a unit-less "deviation of nominal value" of a system state parameter (voltage profile or line loading) is shown over several time steps Δt. The magenta line shows the initial state S_i of the system parameter. It is the grid behaviour without any intervention of the DSO agent. The thresholds L_1 and L_2 are represented as dashed lines in orange and red respectively.

In the time steps t_1, t_3 and t_7 this deviation in the initial state is smaller than L_1 and the system stays in the green phase. No further actions are taken of the operation management system and S_r is close to S_i.

For the time steps t_2, t_4, t_5 and t_6 the deviation in S_i would violate limit L_1. Thus, according to the traffic light concept, the system transitions into the amber phase and the DSO agent uses the provided flexibilities to react to the situation. For time step t_2 the agent is fully successful and the system returns below L_1 in the resulting grid state S_r.

For the time steps t_4 to t_6 the effect of the integrator has been visualised. Before time step t_6, the system has already been in the amber phase. At t_6 the sum of the deviations of the previous two time steps has reached a critical value. Consequently, a federation is built with a neighbouring cell and together, with more flexibility available, the overall system state is improved.

In t_8 the initial state would exceed L_2, so the system switches to the red phase, and the DSO can interfere more extensively with the grid operation to return the deviation below the thresholds.

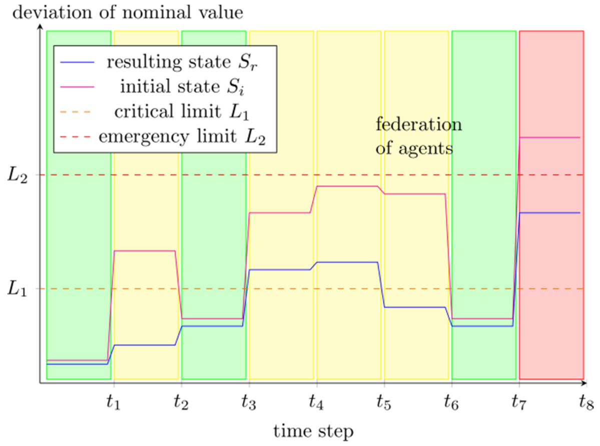

Figure 5 Schematic behaviour of grid operation management according to the power system traffic light

Interaction of Agents

The interaction between agents in the grid changes according to the current grid phase(s). This is mainly related to the way the set points issued by the optimisation are transferred to the affected prosumers, see Figure 6.

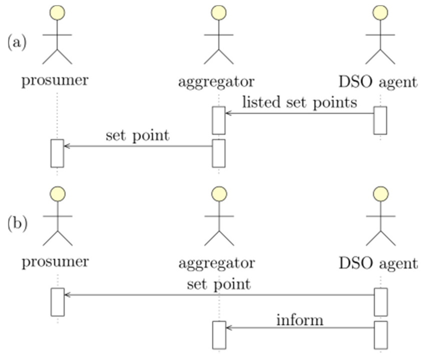

Figure 6 Agent interaction when communicating the set points in amber (a) and red (b) phase

In the amber phase the DSO agent transfers the new set points to the aggregator, who hands them over to the prosumers (see (a) in Figure 6). This communication path is the preferential one, as it respects the unbundling. Nevertheless, in an emergency situation (red phase) it is important for the DSO to have direct access to the prosumers and impose certain behaviour directly on them, see (b).

CONCLUSION AND OUTLOOK

A concept has been developed for an agent-based decentralised distribution grid management based on the concept of a traffic light. It can react adaptively and locally on different grid situations and violations of system limits. This allows an operation where market mechanisms are not necessarily suspended globally in case of a local emergency but only for the affected parts of the grid. A control mechanism increases the stability when conflicting local decisions are taken. Several use cases have been described to illustrate the scope and flexibility of our approach.

The system is currently implemented and tested in an integrated simulation environment and will be implemented on a test site in a French distribution grid as part of the European project DREAM [11].

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REFERENCES

[1] European Electricity Grid Initiative, 2013, “Research and Innovation Roadmap 2013-2022”

[2] M. Amin, 2001, “Toward Self-Healing Energy Infrastructure Systems”, *IEEE Computer Applications in Power*, issue 1, 20 – 28

[3] S. D. J. McArthur et al., 2010, “Multi-Agent Systems for Power Engineering Applications—Part I: Concepts, Approaches, and Technical Challenges”, *IEEE Transaction on Power Systems*, vol. 22, issue 4, 1743 - 1752

[4] P. Leitão, P. Vrba, T. Strasser, 2013, “Multi-Agent Systems as Automation Platform for Intelligent Energy Systems”, *Annual Conference of the IEEE Industrial Electronics Society,* 66 - 71

[5] K. Moslehi, A. B. R. Kumar, D. Shurtleff, M. Laufenberg, A. Bose, P. Hirsch, 2005, “Framework for a Self-Healing Power Grid”, *IEEE Power Engineering Society General Meeting*

[6] S. B. Ghosn, P. Ranganathan, S. Salem, J. Tang, D. Loegering, K. E. Nygard, 2010, “Agent-oriented Designs for a Self Healing Smart Grid”, *First IEEE International Conference on Smart Grid Communications (SmartGridComm),* 461 – 466

[7] H. Liu, X. Chen, K. Yu, Y. Hou, 2012, “The Control and Analysis of Self-Healing Urban Power Grid”, *IEEE Transactions on Smart Grid*, vol. 3, issue 3, 1119 – 1129

[8] R. Caire (ed.), 2014, DREAM reference object model and dictionary, Deliverable 5.1 DREAM-project

[9] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2013, “BDEW-Roadmap - Realistic Steps for the Implementation of Smart Grids in Germany”, Berlin

[10] E. Drayer, F. Meyer, J. Hegemann, M. Braun, 2015, “Control strategies for a decentralized, real-time operation of distribution grids”, *accepted for 2015 IEEE Eindhoven PowerTech*

[11] www.dream-smartgrid.eu, 2015/01/01