Distributed Renewable resources Exploitation in electric grids through Advanced heterarchical Management

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ABSTRACT:

This document describes the scientific and technical barriers and challenges that have to be solved for a successful development of the DREAM framework from a real-time control perspective. The first part of the document is dedicated to a short analysis of scientific barriers that need to be overcome and in the second part an introduction to the DREAM methodology and main scientific advances proposed by the distributed agent-based DREAM framework are given.

[1] PU = Public; PP = Restricted to other program participants (including the ECservices); CO = Confidential, only for members of the Consortium (including the EC services); RE = Restricted to a group specified by the Consortium (including the EC services).

2 R = Report; R+O = Report plus Other. Note: all "O" deliverables must be accompanied by a deliverable report.

3 Filename must follow the semantic defined in the Handbook (eg DX.Y_name_v0x). v1 corresponds to the final release number.

Internal report Contributors[4]**:**	Name	Organisation	Role / Title
Internal Report Leader[5]	Elisabeth Drayer	Uni Kassel	
Contributing Author(s)[6]	Elisabeth Drayer Jan Hegemann Martin Braun	Uni Kassel	
	Iasonas Kouveliotis-Lysikatos (esp. Section 2.2.2.1)	ICCS	WP 4 leader
	René Kamphuis (esp. Section 2.4)	TNO	WP 5 leader
Reviewer(s)[7]	Martin Braun	Uni Kassel	
	Bruno Lisanti Tayyab Abbas Shamsi	ActValue	WP 10 leader
	Marc Lazarus	ESR	WP 9 leader
	Francisco Ramos	Telvent	WP 6 leader
Final review and approval by Coordinator	Raphaël Caire	Grenoble INP	Project coordinator

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4 Refer to the DREAM Management Handbook for more details on the IR Process and roles of contributors.

5 Person from the lead beneficiary that is responsible for the deliverable.

6 Person(s) from contributing partners for the deliverable.

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Executive Summary

This document presents the scientific advances to enable distributed direct real time control at the distribution level. To do so, a brief analysis of current development is introduced, that is followed by a description of barriers that need to be overcome by the DREAM project to enable the successful distributed real time control. Here we focus mainly on this control perspective, but the mutual dependencies to the day-ahead and intraday strategies as well as the operation planning shortly before real-time cannot be underestimated.

The identified scientific barriers can be summarized as:

- Coordination of strategies in different operation mode for a distributed management system
- Appropriate strategies that fully use this distributed management system
- Levels of DSO control
- Robustness and ICT security

In this document not only the scientific barriers are presented, also the methodology and concepts to overcome these barriers are described.

The main developments will be done concerning the coordination of strategies in different operation modes as well as the development of these strategies to provide specific functionalities to the grid management framework that is dedicated to support the evolving role of DSOs all over Europe. Based on a multi-agent system, this management framework will use innovative ways like bottom-up approaches, distributed and decentralized multi-objective optimizations, dynamic federations and peer-to-peer negotiations to fulfil the requirements. Furthermore, not only the development of strategies is an important issue but also the correct deployment of them as well as the analysis of interactions between distributed strategies. In a given situation, which method can and should be used to achieve a desired result, and how can these methods benefit the most from the agent-based and distributed system they are part of? This will also include a dynamic hierarchy and changing communication and interaction paths depending on the needs of the grid.

However, the distributed multi-agent system bears the risk of leading to inconsistent and oscillating situations, as different parts of the grid can be in different modes and counteracting methods could be performed by neighboring agents. So not only the operation mode must be considered but also the interaction mode, and control mechanisms must be incorporated.

While the aim of DREAM should be a fully automated system, methods must be provided to allow the DSO at any time to take over manual control over the whole system or on parts of it. Apart from these very specific issues several important questions need to be answered when developing such an operating framework, mainly concerning the robustness of decentralized solutions and their security against cyber-attacks.

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Glossary of Terms Used in this Document

For a full glossary of terms and how they are used within the DREAM project, see the publication D5.1 "DREAM Reference Object Model and Dictionary" [DREAM-D5.1]

Introduction

One aim of the DREAM-project is the development of the real-time operation strategies for the DREAM management framework to support the evolving roles of the DSOs. This means, based on a certain prevailing situation in the grid, which is represented to the decision-making unit by measurement data, the management framework takes specific actions to change this situation and avoid a contingency and therefore enforces the robustness of the grid. The scope of such situations ranges from a local voltage violation in the far end of a LV feeder due to distributed energy generation to the region-wide re-establishing of the MV grid after a fault. Based on a multi-agent system, this management framework will use innovative ways like bottom-up approaches, distributed and decentralized multi-objective optimizations, dynamic federations and peer-to-peer negotiation to fulfil the requirements. Indeed, decentralization of intelligence can be seen as another strategy of coding advanced distribution automation functions but, can be seen as well as an opportunity to manage distributed resources as much and as locally as possible, and enable their active participations to unbundled and open energy and ancillary services markets.
Furthermore, not only the development of strategies is an important issue, but also the correct deployment of them. In a given situation, which method can and should be used to achieve a desired result, and how can these methods benefit the most from the agent-based and distributed system they are part of?
These are the two main questions from a real-time perspective that need to be answered, the main barriers that need to be overcome for a successful implementation for the DREAM framework. They arise also for day-ahead and intra-day operation planning. But in these cases there is still time to validate and correct the solutions until they physically came to pass. However, for real time, possible interferences between the strategies of different distributed agents could lead to catastrophic grid situations. This has to be anticipated and treated in advance.

The research area "Smart Grids" with all its neighboring branches of research is very dynamic and fast evolving. Everywhere in the world scientist from universities, research centers or industries are working hard to find new ways for organizing and rationalizing our energy generation, transportation, distribution and consumption. Projects that unite several partners from different European countries, with different backgrounds and funded by the European Commission have been at the forefront of this development. [EuropeanComission2014] While certainly not being an exhaustive list, the following projects should be mentioned as there results have been highly inspiring for the DREAM project: FENIX (**F**lexible **E**lectricity **N**etworks to **I**ntegrate the e**X**pected Energy Evolution), CRISP (distributed intelligence in **Cr**itical **I**nfrastructures for **S**ustainable **P**ower) and INTEGRAL (Integrated ICT-platform based Distributed Control in Electricity Grids)
FENIX was launched in 2005 with 4 year runtime and was built of a consortium of 20 partners from 8 European countries. The main result of the FENIX project was the development of the concept of Virtual Power Plants (VPPs), and their technical, commercial and regulatory investigation. [Corera2009]

The objective of CRISP was to investigate how "the latest advances in distributed intelligence by information and communication technologies (ICT) can be exploited in novel ways for cost-effective, fine-grained and reliable monitoring, management and control of power networks that have high degrees of distributed generation penetration." It took place from 2002 to 2006 and united 6 partners. [Akkermans2006]

The third of the aforementioned projects, INTEGRAL, can be considered the spiritual predecessor of DREAM. Its main goals were to show "the practical validity of Smart Grid ICT solutions by three field demonstration [...] that together cover the full range of operating conditions: normal, critical and emergency conditions.” [Integral-FinalBrochure2011] More details on the main ideas of INTEGRAL and how they relate to the current DREAM project will be given in Section 1.1.2.

The following deliverable will be structured as follows: Chapter 1 gives a short overview of recent developments on relevant topics concerning the functionalities of the DREAM framework and an analysis of the mayor barriers that need to be overcome. In the second chapter the methodologies for the proposed DREAM developments are described as well as an introduction to solutions proposed by DREAM to overcome this barrier.

1. Analysis of Scientific Barriers

The following chapter identifies the main scientific barriers that arise from the state-of-the-art of development and innovation. The DREAM framework, a management framework to support the evolving roles of the DSO will be realized as a distributed agent-based system. The first part of this chapter takes a look on important recent developments on which the DREAM framework can be based concerning the implementation of appropriate methods and strategies as well as their deployment and coordination according to the needs in the grid. Based on that, the major scientific barriers are identified.

1.1. Coordination of Strategies

The DREAM framework will be realized as a distributed agent-based system that can evolve between distinct operation modes. So a closer look has to be taken on developments concerning agent-based grid management and the use of different operation modes to coordinate the behavior of the system.

1.1.1. Agent-Based Grid Management

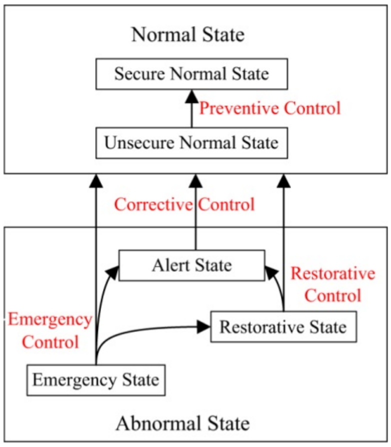
According to the European technology platform “smartgrid” a “self-healing” grid is a “network with high level of decentralized preventive control and outage management combined with automated network restoration” [EuropeanComission2007]. It is the aim of the DREAM project to realize such a self-healing control based on a multi-agent system compatible with an open market approach to enable and ease active participation of end-users and distributed energy resources. But we are not the first to consider this idea. So far as we know, the first comprehensive vision on that subject was given in [Amin2001] in the year 2001.

In [Moslehi2005], [Ghosn2010] and [Liu2012] concepts and frameworks for an agent-based self-healing power grid are described. The ideas developed are quite similar in their general approach to the scope of the DREAM framework, but as far as we know only parts of such a comprehensive approach really have been implemented and tested in field-tests. In the second part of this document, it will be shown where else the DREAM framework will go beyond today’s state-of-the-art.

The papers mentioned above share the idea of several operating states in which the grid can be, depending on the condition of the grid. Characteristic is the division into three stages (normal, critical or alert, and emergency). In [Liu2012] this idea is expanded into five operating states, see Figure 1.

Dependent on the operating state, certain control actions are carried out. Another important aspect is the structure of the employed multi-agent system. In general it is a combination of a hierarchical and heterarchical approach, as can be seen in Figure 2 (the functionalities displayed are just an example and not a comprehensive representation).

Whilst there still exist several hierarchical layers, there is a heterarchical approach inside each level. In [Liu2012] and [Amin2001] the three layers are called response or reactive layer, the coordination layer and the organization or deliberative layer. The higher the layer, the more intelligent the agent should be, but that generally leads to higher computational demands so hard real-time can only be achieved in the lowermost layer.



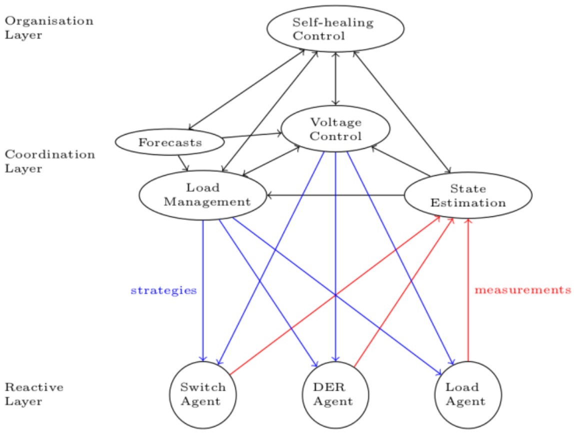


Figure 1 Different operation stages of a power system [Liu2012]

Figure 2 Organization structure of a multi-agent system for power systems [Amin2001]

In [Liu2012] each of the framework functionalities is coupled to a software agent. The paper presents the following list of functions: data pre-processing agent, fault location agent, restoration reconfiguration agent, network topology analysis agent, operation sequence arrangement agent, power flow calculation agent, voltage and reactive power flow optimization agent, "N-1" security analysis agent, static voltage stability analysis agent, short term load forecasting agent, on-line setting calculation agent and electromagnetic loop decoupling agent. So each of the functionalities is outsourced to a dedicated agent. In the work done by M. Khattabi et al. during the E-Energy project Model City Mannheim[9] a different approach was chosen [Khattabi2011]. The management functionalities where split up into just two agents, the market agent and the grid agent. In this context the market agent is responsible for the energy dispatching and the coordination of the energy market participants (similar to the PowerMatcher concept [Kok2005]) whilst the grid agent is controlling and enforcing the compliance of safety margins. As represented in Figure 3, the grid agent takes several inputs like forecasts of generation and load and the market schedule, as well as several measurement data from the grid area he is responsible for (voltage, current, angle). With this information and by performing specific actions he tries to adjust the voltage profile limits, the power factor, etc.

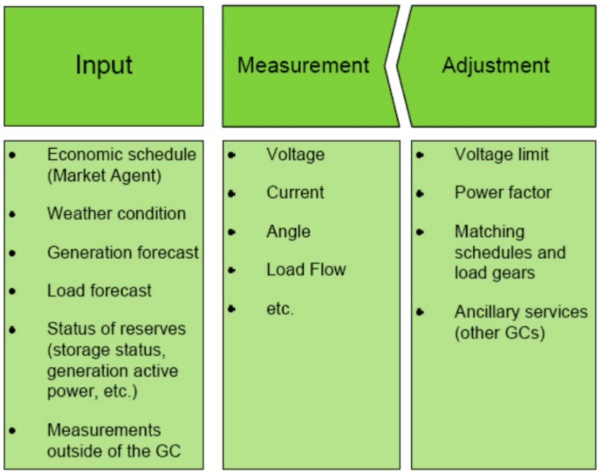


Figure 3 Grid Agent proposed by the Model City Mannheim project [Khattabi2011]

9 http://www.modellstadt-mannheim.de

1.1.2. Operation Modes in the INTEGRAL Project

For the INTEGRAL project three operation modes have been defined, the normal, the critical and the emergency one [IntegralD2.1]. These modes where mainly related to the operation of aggregations of DER and the functionalities such aggregations could provide and were realized in three distinct trial sites.

Under normal operating conditions, the DER aggregation contributed to the reduction of grid power imbalances. Functionalities provided were: long term loss reduction through reconfiguration [Enacheanu2008], intelligent load management through load shedding and load shifting, intelligent DG management through the PowerMatcher concept [Kok2005], coordinated voltage control and optimal power flow [Caire2004] [Richardot2006].

The critical operation conditions arose when upstream MV networks were stressed through overload conditions or other disturbances. In this case, the DER aggregations should show stability when grid-integrated and support the grid though load shedding, voltage and frequency control.

For the emergency case, this means when serious disturbances appeared in the MV grid, self-healing strategies have been developed, this included a fast service restoration and/or possible black start capabilities. [IntegralD2.1]

The described operation modes and the associated functionalities and strategies have been successfully tested in three distinct demo sites A, B and C for normal, critical and emergency operation mode respectively. DREAM will go further and will no longer separate the operation modes strictly from one another but will test the interaction and the transition between different operation stages.

1.2. Multi-Objective Coordination Strategies

1.2.1. Local Control

Local Control especially for PV systems is an approach that is already widely used in the German distribution grid. Up to now, and this trend will continue to last, most of the DERs in Germany like PV and CHP (Combined Heat and Power) are integrated in rural areas [vonAppen2013]. In this context voltage control is one of the most important issues, as the voltage limits are the most likely to be violated. As an answer to this, the German DSOs can choose between three local reactive power control strategies they can demand to be applied. For PV systems they are normally integrated into the inverter [SMA2012].

The simplest strategy is to demand a fixed power factor $\cos\varphi$, that means an automatic cogeneration of reactive power Q depending on $\cos\varphi$. The DSO can fix this power factor between 0.95 and 1. Another strategy is to demand a fixed Q by means of some predefined form of time schedule or by supervisory control signal (only for medium voltage not for low voltage). Strictly speaking, this last method is no longer a local control method. The third approach is to define the reactive power provision via a characteristic. This characteristic can be dependent on the actual power output $\cos\varphi(P)$, or on the voltage at the point of common coupling $Q(U)$. [SMA2012]

Currently ongoing research attempts to further expand the scope of these local control methods into a coupled $Q(U) - P(U)$ control strategy [Stetz2014].

1.2.2. Optimization

Optimization, or more precisely constraint optimization, is the standard way to find the best set of parameters for a system while respecting a set of constraints. In the course of the scientific development, a large variety of approaches have been developed. Most of them have already been used for certain tasks in the power grid, mostly for active and reactive power control. Historically, linear optimizations have been widely used already for centuries, for example in [Shoults1976] and [Mamandur1981]. Linear optimization has a lot of advantages, it is widely used and a lot of methods and efficient solvers already exist, it is fast and the system description is clear.

But in the real world, especially in the power grid, almost nothing has a linear behavior, so the systems and equations have to be approximated and this approximation is only valid for a small interval around the start point. Furthermore, only local optima inside the domain of definition are found.

For "classic" power grid optimizations, like power loss minimization etc. this limitation can mostly be eliminated through adapted problem formulation and linear optimizations lead to practical results. But when cost functions for flexibilities, which are typically not linear, seldom quadratic but mostly not even continuous, also have to be taken into account, the linear approach reaches its limits. Most advanced research in Grenoble INP are exploring with success new reformulations and convexification with some advanced method such as second cone order programing that provides to both reactive power and configuration a successful global research [Toure2013], [Toure2014].

Because the problem description and solving gets very complex and demanding in classic deterministic non-linear optimization, the general trend in recent years has been towards the deployment of metaheuristic approaches. They allow the formulation of extensive problems. But the disadvantage of such approaches is that mathematically it cannot be guaranteed that the algorithm always finds the global optimum. The following section highlights some work already done on this field.

1.2.2.1. Metaheuristic Optimizations

A comparison of different heuristic optimization methods for the voltage control in a distribution grid by the use of flexibilities provided from CHPs, heat pumps, loads and renewable resources was done by [Diehl2013] at Fraunhofer IWES. The aim of this voltage-control is to keep the voltage deviation within a certain range. To do so, agents are placed at the points of common coupling of consumers and producers as well as the substations. As represented in Figure 4, the former generate several buy and/or sale offers for active and reactive power at every time step. Each of these offers has a certain price (positive or negative) that represents how desirable the operational state is for the particular facility. On the superior level (here on the medium voltage level), all the alternatives are collected and those configurations that minimize the objective function are identified by an optimization process. Primary aim is to keep the voltage deviation between ± 3 % of the nominal voltage, the secondary aim is the minimization of costs. For the optimization several metaheuristic optimization methods have been implemented and compared (Particle Swarm Optimization, Ant Colony Optimization, Genetic Algorithms, Simulated Annealing). It became obvious that the Particle Swarm Optimization was both the fastest and best method.

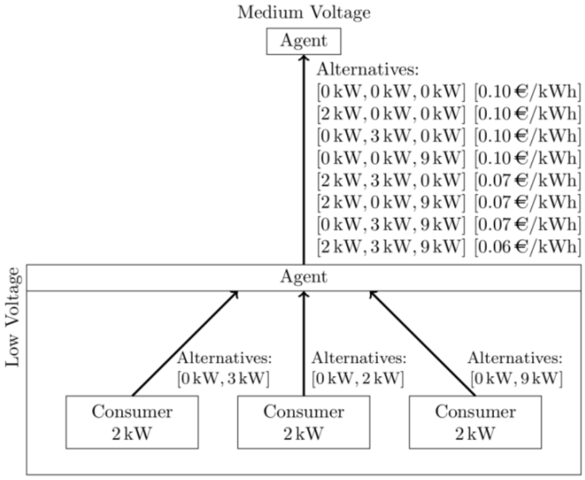


Figure 4 Schema of the agent-based voltage control developed in [Diehl2013]

One more centralized approach has been also developed at Fraunhofer IWES (together with other partners) for the coordinated Voltage control in distribution network as part of the EU-Project HiPerDNO (``High Performance Computing Technologies for Smart Distribution Network Operation'') [Diwold2012]. The idea, as represented in Figure 5, is to carry out a state estimation (DSE for Distribution State Estimation) on the basis of a limited number of measurements. These measurements are taken every 1 to 3 minutes, so a near real-time behavior is achieved. Based on this information an optimization is executed in case of a voltage violation. Parameters of the optimization are the reactive power outputs of the DER, but the approach could be extended to include the active power output and the tap position of an on load tap changer. The algorithm is based upon a Particle Swarm Optimization. It is important to note that some form of uncertainty in the measurement data was included.

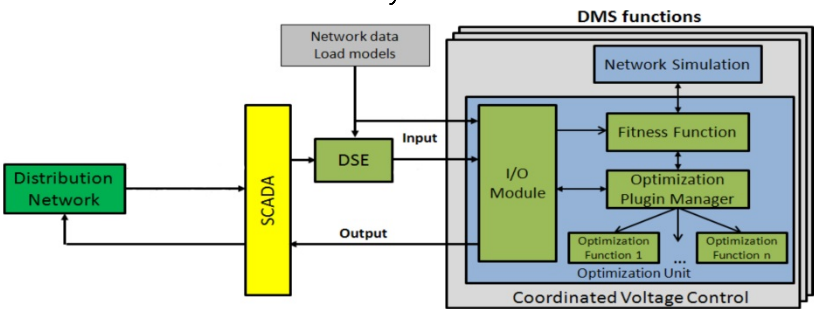


Figure 5 Coordinated Voltage Control developed in [Diwold2012]

1.2.3. Reconfiguration of Power Grid and Power Restoration

Automatic network reconfiguration approaches especially for the distribution grid are investigated for quite some time for the reduction of power losses and load balancing between the feeders [Baran1989]. Since the introduction of more and more automation systems into the distribution grid, simplified on-line reconfiguration methods were developed [Civanlar1988]. Approaches developed more recently are mainly based on heuristic ideas [Tuladhar2014], [Kumar2014].
But these approaches can scale badly when the size of the investigated network is increased and the overall computation time is high [Li2008].
In the DREAM framework the distributed intelligence of the multi-agent structure will be exploited. This will allow a reduction of complexity and therefore allow us to find reconfiguration solutions in near real time. This is especially important for a second case that uses reconfiguration methods, in the power restoration process after a permanent fault has occurred. A permanent fault mostly means that the

circuit breaker at the substation separates the whole feeder from the main grid. The de-energized area can often be significantly reduced by an intelligent network reconfiguration. This means that parts of the grid can be fed by other substations. The first step for such a reconfiguration is to identify the exact position of the fault. In the CRISP-project Grenoble INP has developed a simplified algorithm for the approximate calculation of the fault distance [Andrieu2004]. Based on that and the use of fault passage indicators they developed a method that allows the determination of the exact fault positions in the grid. The next step was the development of a reconfiguration algorithm. This was done by Grenoble INP during the INTEGRAL-project. The idea was to find the grid configuration that maximizes the re-supplied area. In this project it was done by a genetic optimization algorithm [Enacheanu2008]. This concept and functionality has been tested in the micro distribution network at G2Elab [Le-Thanh2009]. Apart from the work of Grenoble INP at least one other paper should be mentioned. In [Nagata2002] the authors developed an agent-based approach to perform a restoration and reorganization of power grids.

1.3. Identified Scientific Barriers

From the previous sections several major scientific barriers could be identified. A power grid can be, and this is especially true for a distribution grid with varying degree of distributed energy resources, geographically be in different stages, according to the client behavior, and the power injection of distributed energy resources. Centralized control concepts can easily reach their limitations, as they mostly cannot react on different needs for different parts of the grid because they can only be in one operation mode at a time. The distributed agent-based approach can be a solution for this, as the agents can react on a more local scope on specific needs in the grid.
One of the most relevant tasks when developing such an agent-based management system is the design of a suitable coordination concept that allows several operation modes, depending on the situation in the grid. According to this operation mode, the methods that are executed are adjusted. The coordination concept should also allow a system where different parts of the grid can be in different operation modes, without leading to instability or oscillation problems.
The second barrier concerns the applied methods and strategies within this coordination concept. These methods should fully exploit and benefit from the distributed agent-based intelligence. Because of this, known concepts have to be adapted and enlarged, leading to a multitude of different strategies, ranging from local, decentralized and distributed to more centralized approaches, providing the best way to react for each circumstance and problem.
The aim of the development is a fully automatic system that could run all by itself. This is a big step for DSOs, as today's distribution grids are mostly operated manually. A barrier, which is both scientific but also requires the rethinking of processes, is the dynamic adjustment of the scope of operation of the management framework according to the needs and wishes of the DSO.

An important issue when dealing with ICT systems is always to ensure the security and robustness of the system. As the power grid is a critical infrastructure, efforts have to be made to guarantee the security and robustness as much as possible. The agent-based approach offers a convenient solution here as well, because it distributes the intelligence and infrastructure. Thus, failure or attacks against it are naturally limited to a small range and impact.

Summing up, the main scientific barriers that have been identified are:

- Coordination of strategies in different operation modes for a distributed management system
- Appropriate strategies that fully use this distributed management system
- Levels of DSO control
- Robustness and ICT security

2. DREAM Methodology and First Solution Proposition

In this chapter the methodology and approaches are proposed that are used to attack and overcome the barriers identified in the previous chapter. This will also include a first solution proposition.

2.1. Operation Modes and Interaction

For the varying aspects of real-time control for the distribution grid, different action strategies and methodologies are developed for the DREAM framework. These cover different situations, problems and tasks. Each of these strategies will be especially useful and effective for solving a particular problem under particular circumstances or for providing a certain service. So, the coordination of these strategies and the selection of the "best solution" at a time is one of the elementary cores of the DREAM framework. Input parameters for this choice are the situation in the grid (measurements) and its topology, the locality (for which part of the grid a strategy is needed) and ancillary knowledge (weather forecast, historic data, etc.) but also the intended objective. The definition of "best" is highly depending on the objective, e.g. is the cost minimal solution wanted or the fastest; sometimes they can be even contradictory. In the context of DREAM the choice of the strategy is a two-dimensional challenge, the choice of operation mode and the choice of interaction mode. In the following sections examples are given how this choice of operation and interaction mode could be realized.

2.1.1. The Operation Mode

The choice of the operation mode is related to the current situation of the grid. The concept proposed for the DREAM framework is inspired by the power system traffic light idea proposed by the BDEW-roadmap for realistic steps for the implementation of smart grids in Germany [BDEW2013]. There, three operation modes are defined, the green mode (normal), the yellow mode (critical) and the red mode (emergency), following the idea of a classic traffic light. Within each mode several strategies for different objectives are defined.
The green phase, the normal mode, stands for a market dominated operation of the distributed energy resources. The energy-contracts placed for day-ahead or intra-day are valid without limitation. The real-time control supervises and evaluates the system continuously, but does not interfere.

For the other end of the power system traffic light, the red phase, also called the emergency mode, the objective function can also be clearly defined. There, the grid stability is in imminent danger and/or flexibilities provided by the Aggregators in a market-based approach are not sufficient to solve the situation. The strategies deployed in the red phase will mostly result in fast, clear and mandatory signals from the DSO, as they are responsible for grid stability. Therefore, the DSO gets major capabilities and authority for this case.

A special position assumes a 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. Clear objectives here are the time it takes to find a solution and the size (standing here not mainly for a geographic dimension but for the sum of the loads) of the re-supplied area.

Between the green and red phase there exists a transition phase, similar to the yellow phase in a traffic light. It describes the critical mode, where the compliance with quality criterions are possibility violated.
The feasible actions that can be taken in this situation use the real-time flexibilities provided by the Aggregator for the DSO but also flexibilities that arise from the grid itself like capacitor banks, OLTC

transformers as well as the grid configuration itself. In this phase the focus of the objective functions can vary depending on the situation and the preferences of the DSO but the forced intervention of the DSO is not intended in this phase, the flexibilities provided by the Aggregators should be sufficient.

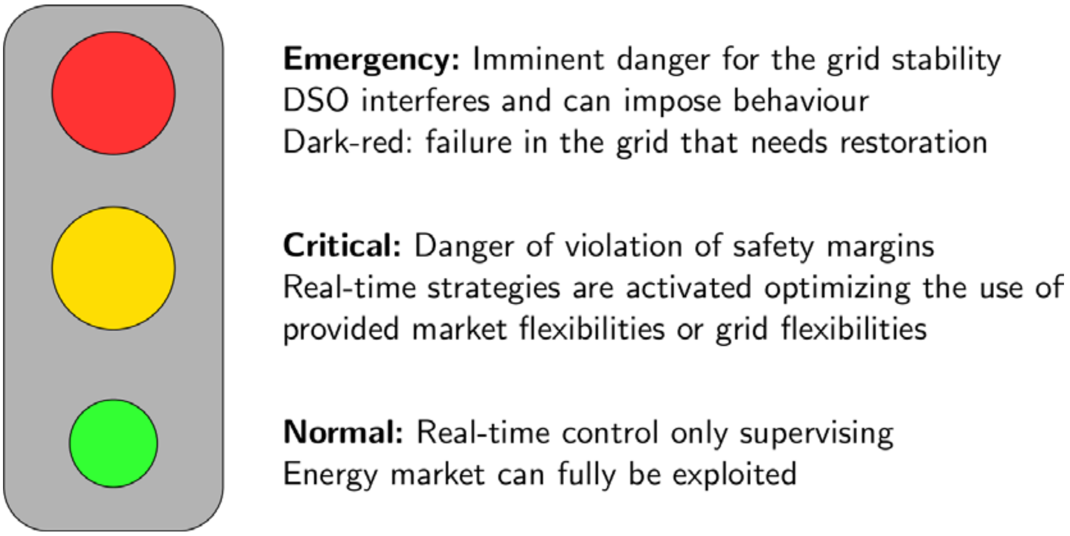


Figure 6 Operation modes in the power system traffic light system

It is important to note that the operation mode can be different for different parts of the grid. Each LV Cell or MV Cell can be optimized separately, that is why there will not be one power system traffic light for the entire grid but several ones, to guide the operation at all the important places in the grid, similar to the traffic lights on our roads. Consequently, this will 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 national or even transnational markets, as it is done today, but local markets will naturally emerge from this distributed control concept.

2.1.2. 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. For example, when the agents, situated at two feeders of the same substation and forced by their local measurements, take actions that counteract against each other. Situations like this could lead to severe stability problems. To avoid all possible negative interferences between agents in a foreseeing manner while developing the strategies from scratch is practically not feasible. Therefore, an important component of the further DREAM framework has to be a control unit that supervises the interactions between the decision taking distributed agents and can interfere if necessary. 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 grid. To solve the last mentioned problem, the commands from higher grid levels always have a higher priority as they take more global constraints into account. As in the end, it is the DSO who is in charge of the grid such a global control unit could be realized within the DMS of the DSO. In Figure 7 an abstract representation of the two different interaction modes is given. The two traffic lights symbolize two parts of the power system, each of them equipped with an intelligent agent. The methods these two agents take can either act in the same direction, leading to a positive interference between the methods or can counteract one another. The first case is desirable and should be encouraged nevertheless attention should be paid that the resulting effect is not overshooting. In the second case the methods will "work" against each other, leading to a reduced effect, or even oscillations and stability problems.

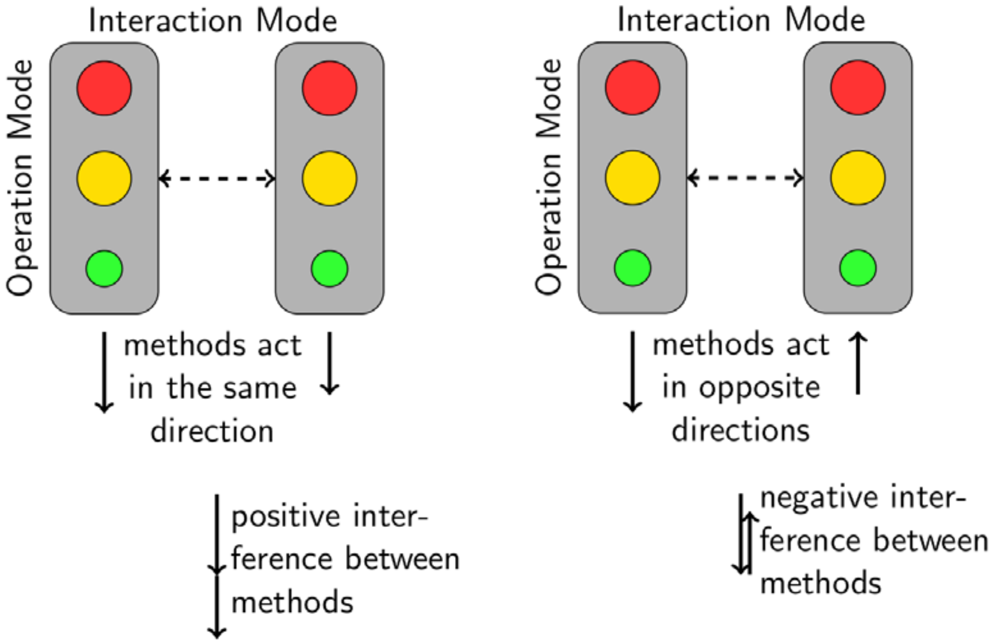


Figure 7 Abstract representation of different interaction modes

2.1.3. Level of DSO Control

The coordination of strategies will be done to optimize the advantages for the DSO. He is granting the stability of the grid, the quality of service for his clients but also the security for the technicians that are working on the field. Especially for the last case the DSO must be in the position to manually switch of parts of the automatic execution of the framework for certain parts of the grid, while in other parts the system is still working. And for extreme and complicated grid situations that require the manual intervention of experienced experts, it must be easily possible for the DSO to switch of certain functionalities or even to shut down the DREAM framework completely. An intermediate step between a fully automated management system and the manual control is a so called semi-automatic mode, where the DREAM framework is normally running but not actually acting on the grid but just proposing the methods to the DSO who can validate them, modify them and/or execute them manually.

2.1.4. First Proposition

In Figure 8 a first simplified draft for the strategies applied in the different operation modes are represented. It is a simplification as several of the strategies that will be proposed by the DREAM framework are not yet validated.

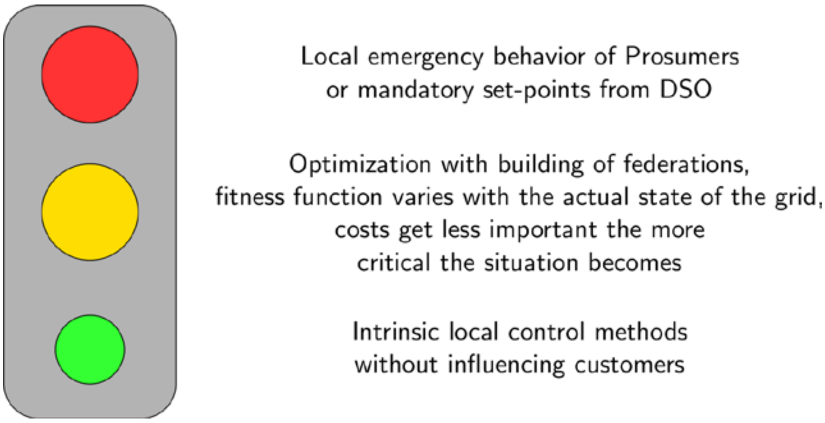


Figure 8 First draft of strategies applied in the different operation modes

In the green phase no active real-time control is executed. Nevertheless, intrinsic local control methods, like reactive power provision of PV-systems or primary and secondary control for synchronous generators, are used according to the rules of the grid code, as they are used "automatically" when the power of these systems is generated.
In the yellow mode optimizations will be performed, taking into account the behavior of grid parameters, but also costs (for power losses as well as the deployed flexibilities) and reduction of reactive power flows.
The main input parameters to this optimization are the flexibilities provided by the Aggregators. If they should not be sufficient for one cell of the grid to solve the problem there, the cells can build federations, to share their flexibilities and to allow a wider optimization. As the situation in the grid becomes more critical, the influence of the costs onto the optimization result is reduced.
In an emergency case, two different approaches can be taken. One is a local action that can be applied when failures in the communication system appeared and the DSO can no longer communicate with its Prosumers. In this case, each Prosumer behaves as is predefined in its internal database. The other strategy is invoked by the DSO who has the possibility to send clear and mandatory set points. These actions will not be restricted on flexibilities provided by the Aggregators.
An important expansion of the traffic light system is that not only the operation mode changes dependent on the situation in the grid, but also the way the different distributed agents are communicating with each other. In the yellow phase the results of the optimization and the desired set points are transferred from the responsible cell DSO to the commercial aggregators (with whom the Prosumers have their contracts). The Aggregator, as responsible commercial partner of the Prosumers, processes the possibly aggregated set point arriving from the DSO optimization and translates it to specific set points for his Prosumers. However, in the red phase, this communication is prohibited. The DSO directly communicates with the Prosumers to imperatively demand a certain set point and the Aggregator is only informed of these changes.

Another example of this changing leadership is the building of federations. As described above, several cells can dynamically build a federation to solve a specific problem with joint forces. Leader of this federation is the DSO of the cell that initiated the federation and the other cell DSOs of the federation follow his direction. While some of the necessary computations will have to be done over the domain of the newly built federation, others may be processed in parallel by the individual cells (e.g. fitness evaluations within the optimization). This leads to a peer-to-peer communication mode between the DSO agents.
It is important to note that the actual phase the system is in does not report the adherence of the system parameters (voltage, current, frequency) to the maximal permissible values. The phase of the system reveals more about how these admissible grid parameters are achieved. In the green phase no

supplemental actions must be taken, whilst in the yellow phase the provided flexibilities are sufficient to ensure the boundary values. In the red phase the DSO does no longer rely exclusively on the flexibility voluntarily provide by Prosumers but can enforce a certain behavior.

However, the transition between the phases will be triggered by the adherence to safety values. Is one of the system parameters evolving near a certain limit, the DSO uses the methods provides for the yellow phase to move the system back in an admissible state. As long as these methods are necessary, the system is located in the yellow phase. The transition between yellow and red phase can be described similarly.

One of the challenges while developing this structure will be the definition of the threshold value, between the phases. Here an approach similar to the time-current-characteristic of overcurrent protection devices will be chosen. Depending on the height of the violation of the boundary value and the length of this violation either the red or yellow phase is chosen, see Figure 9 for a schematic representation.

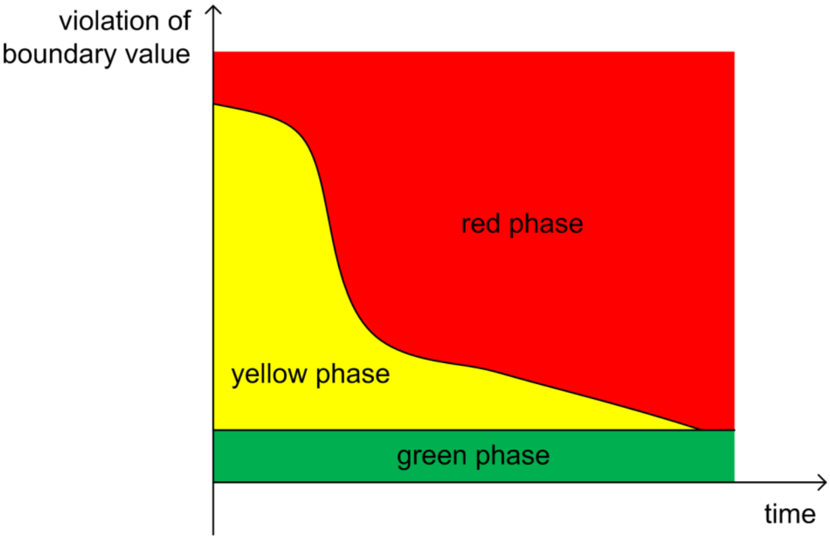


Figure 9 Transition between the system phases

In Figure 10, a possible form of interaction control is schematically represented for two MV elementary Cells. Each of them has their one traffic light system, and can take distinct actions. Both the neighboring MV elementary Cell DSOs as well as the overlying agent level, here the substation DSO agent, are informed about these actions. If the strategies go in the same direction, e.g. both MV elementary cells have a similar problem (e.g. overvoltage) they can build a federation to coordinate their approach and to find a “more global” solution. When the strategies could potentially counteract one another, the substation DSO agent takes over the lead and tries to solve the problem from a superior point of view.

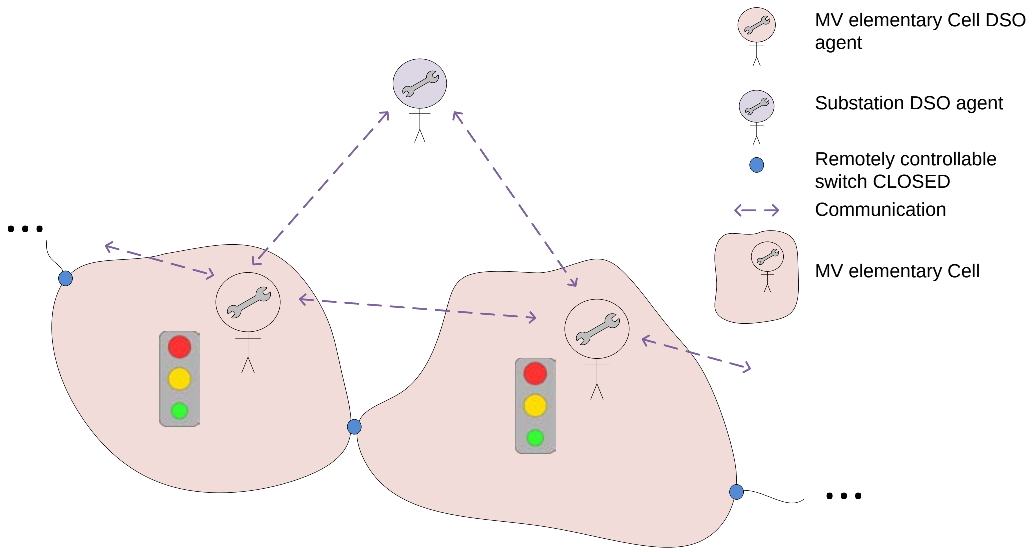


Figure 10 Possible realization of interaction control

2.2. Multi-Objective Coordination Strategies

As already highlighted in the previous section, the strategies that will be applied for the solving of specific tasks and problems are many-sided. On the one hand this is possible because of the dynamic flexibility of the distributed agent-system. On the other hand it is an appropriate way to response to the varying conditions and structures in the different distribution grids all over Europe. Because of the different structural shape and the varying degree of DER integration and use of electric cars in different distribution grids, the requirements and input parameters for the available methods as well as the tasks that need to be addressed and the problems that might occur can drastically vary. This huge challenge will be solved by a multitude of different coordination strategies that implement methods that differ in objectives, constraints and parameters. The choice of the strategy will be taken according to the operation and interaction mode presented in the previous section and will lead to a method that is applied.
The following paragraphs will present some aspect and advances for the main methods included in the DREAM framework for real-time control.

Concerning the general approach, one can distinguish three groups of methods:

- Local control of Prosumers and grid entities
- Optimization of flexibilities
- Grid reconfiguration

2.2.1. Local Control

As described in the first chapter, local control of Prosumers, mainly for PV systems, is widely applied in Germany [vonAppen2013]. This is primarily done to solve local voltage problems in low voltage grids with high penetration of PV systems or at the end of long lines through injection of reactive power. The amount or characteristic of this local reactive power injection can be defined in several ways. State-of-the-art in Germany is a fixed cos(φ) ratio between P and Q. Possible are also Q(P), Q(U) and P(U) characteristics, the latter two are intensively investigated at the moment [Stetz2014]. For the DREAM-framework it is essential to embed this local control fruitfully into the agent-base context with the possibility to update the characteristics within the running system but also to disable and control this local strategy in the case of interferences, or better and more global solutions. To do so, the Prosumer applying the local control will inform his overlying DSO agent about it, so that the DSO has as much knowledge as possible of the current situation of the grid.

2.2.2. Optimization

In the DREAM framework the optimization process will be extended for a multi-agent environment and use its distributed intelligence. Each elementary cell can solve their problems through optimization. Is this not possible, a federation of elementary cells is dynamically built with the neighboring cells to have wider optimization possibilities. The optimization will take the multi-dimensionality of the power system into account, with the possibility to focus on different objectives according to the specific needs and the situation in the grid. The considered objectives and constraints will include the adherence to safety margins of voltage and current, the power losses, or more generally the cost, the quality of service and the form and availability of flexibility and their quality. To ensure the adequate treatment especially of this last parameter and the complex behavior it might have, a metaheuristic approach will be chosen. This has a second advantage, as some of the metaheuristic optimization methods (e. g. evolutionary algorithms, particle swarm approaches) can be easily parallelized. Especially for the case where the optimization is done for a federation of elementary cells, several “intelligent” agents exist and the optimization can be parallelized. A special case will be the distributed optimization.

2.2.2.1. Distributed Optimization

An optimization problem includes finding the "best available" values of some function (often called the objective function of the problem) given a defined domain or a set of constraints. Depending on the mathematical formulation of the optimization problem a variety of different types of objective functions and different types of domains can be incorporated. More specifically, the process of solving an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function.

In some cases it is possible to decompose the optimization problem into subproblems. These subproblems can be distributed among a set of autonomous and intelligent communicating entities (i.e. agents), each one controlling its own subproblem. It is also possible for certain agents to have privacy concerns, in a way that they are willing to cooperate in order to find a good solution for every subproblem (achieving therefore a global optimum), but they are reluctant to divulge private, sensitive information.
For instance, producing complex goods like cars or airplanes involves complex supply chains that consist of many different actors (suppliers, subcontractors, transport companies, dealers, etc.). The whole process is composed of many subproblems (procurement, scheduling production, assembling parts, delivery, etc.) that can be globally optimized all at once, by expressing everything as a constraint optimization problem [Petcu2009].

Such problems can be solved in a centralized fashion where all the information of the subproblems was communicated to one entity and a centralized algorithm was applied in order to find the optimal solution. In contrast, a distributed solution process does not require the full information knowledge of every subproblem. The agents involved preserve their autonomy and control over their local problems. They communicate via messages with their peers in order to reach agreement about what is the best joint decision which maximizes their overall utility. Centralized algorithms have the advantage that they are usually easier to implement, and often faster than distributed ones [Petcu2009], but distributed algorithms for optimization problems eliminate the need to transmit raw data to a central fusion center. This can provide significant reductions in the amount of communication in order to reach the optimal solution.

For instance, the technical and economical optimization of modern distribution systems is a challenging and very complex problem. The drastic increase of distributed generation connected at the distribution level, imposes the necessity for the application of distributed optimization methods in order to avoid the large exchange of information that a centralized approach requires.
The current technological advancements in the field of telecommunications imply that a peer-to-peer scheme can be used. More specifically, technologies such as RF, PLC and Zigbee incorporate the concept of information broadcast which is innate in algorithms with peer-to-peer information exchange. For this reason it is considered that such technologies along with Advanced Meter Infrastructure (AMI) systems lean to peer-to-peer applications.
This development provides a new insight in power system operation, where every entity equivently shares the responsibility for the operation optimization while communicating solely with its neighbors.

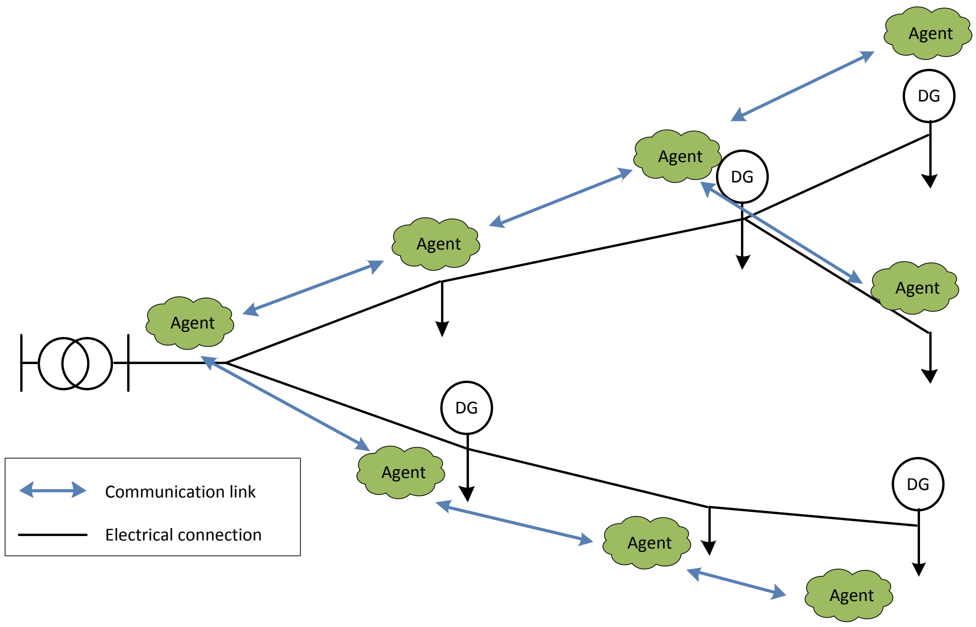


Figure 11 Distributed agent-based optimization of an distribution network with increased DG penetration

Therefore, a distributed optimization algorithm should be able to optimize the distribution grid operation, reconciling economical and technical constraints with information exchange only between adjacent nodes. An example of such a scheme is given in Figure 11.

In this context, distributed optimization algorithms can enable the implementation of distributed control strategies. Due to their properties, gossip algorithms can be successfully implemented in systems where actors have only local knowledge and are able to communicate with neighboring actors. By means of these interactions and using the shared knowledge, the actors can complete tasks that enable achievement of global objectives [Krkoleva2011]. Gossip algorithms have already been used for the purposes of secondary and tertiary control for Microgrids, as explained in [Brabandere2007].

2.2.2.2. Flexibility Release

After an optimization has found a new set of parameters for the provided flexibilities and grid entities like OLTC, these set-points can be communicated in different ways to the particular entities. A practical example has already been given in Section 2.1.4. where the distinction has been made between the way the set points of the DSO optimization are transferred to the Prosumers. In the yellow phase they pass via an intermitted commercial Aggregator, in the emergency case (red phase) the communication is directly between DSO and Prosumer to allow direct control of the DSO.

2.2.3. Grid Reconfiguration

Medium voltage grids are often build as ring or meshed systems, but are operated as radial grids as the protection devices can be simplified and the grid operation is easier to supervise. However, in certain circumstances this allows the reconfiguration of the grid, especially for long term and often occurring overload situations but also for the elimination of failures. In a moderate way, it is already done today based on reconfiguration tables calculated in advance for a collection of failures and outages. With a growing number of distributed, fluctuating generators this is no longer readily possible as the effective loads and current directions can heavily change, and a multitude of operating states have to be evaluated. DREAM will develop an agent-based, distributed strategy for failure detection and reconfiguration, specialized for fast and time-critical situations. It will be based, among other possibilities, on some branch exchange methods and successively enlarge the investigated grid until a practical solution is found. This can naturally lead to sub-optimal local solutions, but when time is a hard constraint, it is more important to have a good solution then to have the best solution, that comes too late.

For all methods the DSOs stay in the loop as last authority, as they carry the responsibility for the grid. In an emergency case he can interfere quickly and directly (this includes the selective start and stop of load and generators, as well as the DREAM framework) and take over control manually. This is especially important for maintenance work in the field but also against the background of cyber-attacks and software damage.

2.3. Validation though Simulation

As the proposed solution of the DREAM project, the DREAM framework, is aimed for the use in real world test sites in the second phase of the project, they have to be extensively tested before they are installed. This test will mainly be realized by embedding the framework in an appropriate simulation environment.

The complex system composed of the SCADA of the DSOs, distributed RTUs, different communication protocols, etc. in which the DREAM framework will be incorporated has to be represented in an appropriate way. Another challenge is given by the fact that these systems can look quite different for different test sites. In addition to this, due to the distributed agent structure, it is not sufficient to test each strategy separately, but possible interactions and side effects must be taken into account (for further details see Section 2.1.2).

Furthermore, grid information and measurement data are sparse in current realistic power grid environments. Therefore, an appropriate state estimation has to be implemented to provide the necessary information from a set of sparse grid information. This is done by introducing pseudo measurements and using ancillary knowledge of the grid.

Apart from preparing the real live tests, simulations play an important role when it comes to the validation of effects and behaviors that cannot be proven in the field trials. The scalability of the solution is one of the key issues that will be investigated in this way, but also emergency behavior as it might happen that no emergency situation occurs during the tests and no risks will be taken to provoke one by choice.

2.4. Robustness of Decentralized Solutions

Security of supply, resilience and dependability are major features of power systems. Robustness of underlying software systems is a major factor in day-to-day operation of power systems.

The 24/7 power system has 99.9999 percent of the time operational availability requirements (approximately 20-60 minutes outage per year). ICT systems having comparable reliability figures are only found in telecommunication and certain defense sectors. The distributed Internet architecture might be a template of a massively distributed system of system comparable to the future coordination and control system for the power system. The system then is a system of systems where parts join and disassemble continuously.

Agent based approaches have a number of advantages when looking to robustness of the ICT system as compared to top-down controlled systems. As in centrally coordinated power systems, failure of the top-component as in the 2003 New York blackout [NERC2004] does not result in a cascading failure of the total underlying system. Agent-based systems assume implementation in a massively distributed context but from an as confined as possible local context [Brazier2013]. So just as the Internet, agent processes should implement procedures using discovery mechanisms to (re)connect for planned operations and unplanned failures. In the DREAM framework, the static physical configuration of the entities in the electrical network is logically separated from the coordination topology and the coordination algorithm. The latter two can be virtualized and are made dynamic. From a software engineering perspective, this separation also makes it possible to design separate test harnesses for each of these three layers in order to assure extensive module testing. Further research as to resilience and discovery protocols in this area is necessary. In internet technology related ICT systems research these emergent agent aggregation and discovery techniques already are well developed through developments in the Internet of Things.

Another aspect of security is cyber security. In DREAM exposure of loads and generators to markets at lower distribution levels is at stake. Exposure of this market sensitive information to other market parties is a hazard as are the privacy related issues. It has been shown, that the impact of breaches in cyber security heavily depends on the design of the software, but also on the underlying procedures in using the software. Security by Smart Grid design is a major concept to be developed in the ongoing NIST initiative in the US [NIST2012] for secure smart grids. As a first result, a number of obligatory procedures have been formulated for smart meter implementation in the US. In the DREAM framework, distributed intelligence of agents is combined with a possible distributed repository and distributed data storage not using central databases. To meet the cyber security aspects, the distributed nature of the DREAM design, then, has to encapsulate the security sensitive data procedures. At the SCADA-level, in the IEC standard set, adjoining IEC-61850, IEC-62351 that has been defined by TC-57 to handle part of the above aspects; viz. encryption, node and message authentication, security for MMS-usage and for the usage of VLANs if GOOSE is used as a protocol. In the EU-FP6 INTEGRAL [Integral2009] and the EU-FP7 Web2Energy project [Web2Energy-D3.22011] design of tests retaining appropriate security standards in introducing DG-RES and agent technology was one of the research objectives. This combination and hands-on experience has to be extended.

3. Conclusion

In this deliverable the main scientific barriers that need to be tackled on the way to a distributed direct real time control at the distribution level are highlighted and the outlines of the proposed solutions and advancements within the DREAM project have been presented.

The main advances, which have to be made for a successful implementation of the real-time control within the DREAM framework, are the development of a suitable agent-based grid coordination concept that allows several operation modes, depending on the situation in the grid. According to this operation mode, the methods that are executed are adjusted. The coordination concept should also allow a system where different parts of the grid can be in different operation modes, without leading to instability or oscillation problems.

The second barrier concerns the applied methods and strategies within this coordination concept. These methods should fully exploit and benefit from the distributed agent-based intelligence. Because of this, known concepts have to be adapted and enlarged, leading to a multitude of different strategies, ranging from local, decentralized and distributed to more centralized approaches, providing the best way to react for each circumstance and problem.

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5. Appendix: Project Context

The subjects treated in this document are related to two dedicated tasks of the DREAM project: task T3.1.4 “Deployment of behavioral configurations and coordination of actual operations” from WP3 and task T4.1.1 “Multi-objective coordination strategies for contingency management”.
Although T3.1.4 is part of WP3 it is covered in this document (that is dedicated to WP4) because especially for real-time operation the choice of optimal operation strategy is the most demanding challenge.