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# Fractal Grid – towards the future smart grid

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**Abstract:** In the last two decades, electricity grids have faced many challenges that they were not designed to handle. These include integrating weather-dependent renewables, distributed generators, storage units and other advanced components, as well as taking into account active demand. These challenges, together with the ageing of infrastructures, make it more difficult to deliver cost-effective, reliable power. To overcome these issues requires creating new network architectures. The research project Fractal Grid proposes fractality as a core concept to model, analyse and design smart grids in their evolution up to 2030 and beyond. This study presents the project, its methodological approach and the first results.

## 1 Introduction

Increasing awareness of the environmental impact of conventional energy sources and the advent of power system deregulation has shaped the direction of power system technology. To encourage the transition to a safer, more sustainable and decarbonised energy system, the European Commission Energy Roadmap for 2050 has set climate and energy targets [1]. The development of a reshaped power system with a forward-looking climate policy is one of the European Union's strategic objectives. Reshaping will accompany massive integration of renewable energies and storage devices and, on the load side, a greater share of controllable and active loads, i.e. thermal loads in residential and industrial sectors and electric vehicles [2]. Moreover, the uptake of smart meters and smart transformers into power grids, as well as all the intelligent functions needed for their management, represent a key challenge to move towards the future smart grids.

Fractal Grid is a research project whose main objective is to propose new network designs for future smart grids in their evolution up to 2030 and beyond. The first two sections of this paper present the state of the art of future grid architectures and the project's methodological approach. The last section gives some preliminary results of the project including examples of the considered use cases.

## 2 State of the art

Long-term scenarios for the European system show a strong increase in electricity production and a high growth of electricity demand [3]. The development of power systems is also driven by the rising use of fast-reacting distributed resources and electrical storage devices to provide reserve capacity, by the implementation of innovative sensors [4] in order to increase the power system's observability, and by the integration of information and communication technology. This fast evolution has raised many challenges requiring complex electrical system modelling and advanced system design. A third key issue is to ensure the interoperability of future smart grids.

According to [5], the feasible functional architectures for the future require either centralised or decentralised management. Web-of-Cells architecture, developed in the frame of the ELECTRA project, converges towards a decentralised management scheme. With this architecture, the power system is divided into cells and the operator of each cell is responsible of its real-time balance, frequency and voltage control. Cells can include different voltage levels and are connected to each other via inter-cell physical tie lines.

The multi-micro-grid concept represents another emerging architecture. This system is a medium-voltage structure, consisting of several low-voltage (LV) active networks, aka micro-grids, distributed generation units, controllable loads and storage devices. The management and control of a multi-micro-grid is ensured by hierarchical control architecture. Each micro-grid, managed by the micro-grid central controller, communicates with the distribution management system (DMS) designed to monitor and control the distribution network [6]. In high-voltage (HV)/ medium-voltage (MV), centralised autonomous management controllers are deployed at voltage stations to handle the scheduling problems of distributed generation units and communicate with other local controllers [7].

The research project, Fractal Grid, aims at proposing a new architecture paradigm for smart grids based on fractality. Indeed, self-similarities of territories and power systems have been observed [8]. Moreover, these authors assume that future power systems will become organisationally fractal, consisting of the recursive assemblage of many smart buildings, micro-grids, smart cities, distribution grids, national and international networks [9].

Fractal grids need to yield a more flexible, controllable, resilient and interoperable electrical system enabling efficient and safe operation. To respond to this, the project methodology 'goes back to basics' and develops an innovative multi-scale methodology to address the increased complexity of future power systems.

## 3 Methodology

The major methodological challenges that will be addressed by Fractal Grid are multi-scale modelling and design. 'Multi-scale' means that the project will consider aspects ranging from weather systems and market organisation down to electrical network

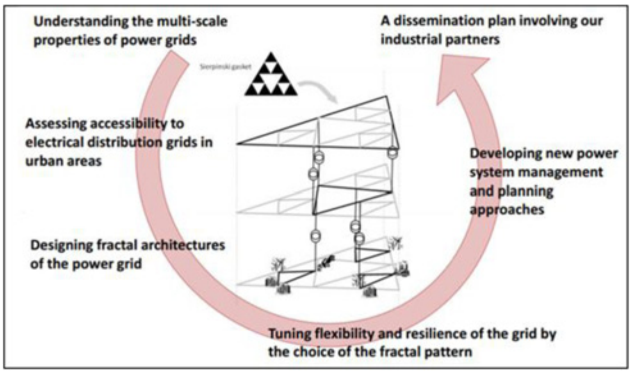


**Fig. 1** *Research directions of the Fractal Grid approach*

topologies with a particular focus on the latter. Key points of the project methodology are shown in Fig. 1.

Multi-scale approaches can also be used to analyse power transmission as distribution systems. In Fractal Grid, we will first focus on distribution systems covering inter- or intra-urban territories. Some links will be made with the upper level system to study the vertical interactions inside the global electrical network. However, we will not go beyond the regional scale.

Fractal Grid could consider either Greenfield or Brownfield approaches. In the first case, the planning will not consider any constraint linked to pre-existing buildings or architectures (example of the development of a new urban zone). In the latter one, one must take into account the structures already in situ.

### *3.1 Understanding the multi-scale properties of power grids*

Multiple research results have shown that built-up space is often structured according to fractal logic and recent investigations have compared the coherency between the spatial organisation of urban built-up spaces and street networks [10]. A similar approach is suitable for power systems. A given built-up area corresponds to an optimal topology of the power grid. This results from the spatial distribution of power sources and loads, the technical constraints, such as the maximal voltage variations, and the global cost. This latter cost is the sum of three components: the investment cost, the power loss cost and the non-supplied energy cost if the network is not reliable enough. Of course, the optimal solution is highly dependent on the spatial arrangement of the built-up area. Multi-scale analysis aims to characterise this dependency at different scales of observation and determines how it influences the optimisation of the power grid topology. For this purpose, the fractal dimensions of built-up areas are computed. These dimensions characterise how the built-up areas fill the space. Moreover, fractal analysis identifies scales in which spatial organisation changes. To identify ruptures or shifts in the scaling behaviour, a special method has been developed for urban pattern analysis [10]. A similar analysis can be performed for electrical distribution networks. This analysis can improve our understanding of the spatial organisation of the distribution network on inter-urban and intra-urban scales and identify hypertrophies or deficiencies in existing networks. For instance, it intends to study the link between spatial distribution of consumers or decentralised energy sources in urban areas and network morphology.

### *3.2 Assessing accessibility to electrical distribution grids in urban areas*

Beyond standard fractal analysis methods, a couple of specific methods adapted to networks and originally used in materials science, like percolation or multi-fractal formalisation [11], are applied. These methods allow us to e.g. explore the properties of the most direct path between two nodes and the distribution of meshes, which render the network more robust but also tend to increase the cost. Moreover, they can take into account simultaneously the topology of the network, its power flow and the multi-scale distribution of voltage drops. Then, taking voltage drops as a measure of power accessibility quality (the lower the voltage grid, the better the service provided by the electrical system), it is possible to assess accessibility to electrical distribution grids over a given area. All of these results are used to reshape the architecture of smart grids.

### *3.3 Designing fractal architectures of power grids*

Fractality is used to design new smart grid architectures. This design is driven by the assumption that a self-similar topology can benefit the electrical system, from consumers to utilities. Indeed, nature shows that fractal networks emerge when a minimal guarantee of continuous supply is required while minimising the space covered by the network. On the other hand, minimising the coverage of a network decreases its resilience since the connectivity is reduced. However, fractal structures are often made up of multiple loops at different scales. This increases the network's resilience to link damage. Fractal structure can thus be the optimal design solution.

Hence, the objective is to design a fractal architecture for an urban distribution system. First, a built-up area is chosen from the open-access geographical information system database provided by IGN (IGN: National institute of geographical and forest information in France). Over this area, data concerning network geometry, substations at the HV/MV and MV/LV grid interfaces, cables, loads and dispersed generators are collected from the distribution system operator (DSO). Then, a number of fractal patterns (meshed or radial) are tested and adapted to interconnect substations, dispersed generators and loads and provide an optimal operation of the electrical system. The design aims at multi-scale coverage of the built-up area. This means that the spatial organisation of the electrical grid shall correspond to the needs and constraints of users located in the considered area. For this purpose, the results provided by the previous steps of the methodology are very useful. Finally, the cross-scale interactions between the designed Fractal Distribution Grid and the regional grids, which are connected at the HV/MV interfaces, are studied.

### *3.4 Tuning the grid's flexibility and resilience through the choice of fractal pattern*

An important property of smart grids is their resilience, i.e. their ability to survive perturbations, repair themselves and adapt to new situations. In Fractal Grid, we address the robustness and adaptability of the network using tools from graph theory, optimisation and control theory. Random faults, broken links and power surges impact the network differently depending on its topology and the configuration of the generators and loads. This is mainly a static optimisation problem: in time and space. Important questions are: can a load-flow solution exist if a given link is broken? Which network topologies are most resistant? A number of studies in the complex network literature [12] link the graph topology of the network to its robustness and answer the main question, which nodes or links are most critical? We can apply these methods to power systems and compare their predictions to the load-flow calculations. Then, the results of the study guide the design of fractal architectures according to resilience criteria.

From another point of view, the adaptability of a network is a dynamical property because the network needs to shift from one state to another while it is in operation.

Using spectral properties of electrical networks, we have identified soft nodes for which no control or observation is possible [13]. Of course, future smart grids will need to minimise the number of soft nodes in order to increase their adaptability. Soft nodes for the designed fractal architecture are therefore identified by the same approach and the new issue is to show whether self-similarities reduce the number of soft nodes.

### 3.5 Developing new power system management and planning approaches

In [14] the challenges facing electric power systems management are identified. Planning and operating the next-generation mix involves making decisions on time scales ranging from several years (concerning new grid expansion) down to time scale scales of fractions of a second. The spatial scales of power systems are related to the sizes of the transmission, distribution, and customer (industrial, residential) systems [15]. It is essential to coordinate distributed energy resources, storage units and active loads in future power systems in order to ensure flexibilities at every level of the system and high reliability. For this purpose, in recent years, several works have proposed hierarchical optimisation [16]. This considers decomposition into sub-systems, which are locally optimised, and the interactions between them [17]. Methods like multi-agent system modelling are seen as a promising technology to perform this kind of optimisation. Although several research works deal with multi-agent systems in the power engineering field, as shown in [18], most only focus on operation at micro-grid and distribution network scales [19–21] or on market modelling and simulation [22–24].

In Fractal Grid, a methodology and a simulation tool based on the multi-agent approach to manage a fractal power system are developed. This considers the major actors in a power system, from the regional system operator to the customer, in a day-ahead and intraday timeframe (see Fig. 2). In addition, the role of electricity markets at the different scales is analysed. Moreover, this simulation tool aims to cover networks with different topologies [15].

## 4 Preliminary results

### 4.1 Multi-scale analysis of a distribution power grid

We performed fractal analysis of two distribution power grids, located in the French administrative areas of Jura and Haute-Saône, which feature both intra- and inter-urban zones.

We compared the power grid with the built-up spatial organisations. To compute the fractal dimension, the results were obtained using the box-counting method, which is a way of determining the fractal dimension by computing the number of boxes used to cover an area. The box size varies to cover different scales. In this case, boxes went from 3 to 27,300 m for Jura and 32,800 m for Haute-Saône. For very small boxes, the fractal dimensions of both Jura and Haute-Saône's distribution power grids were very similar and close to 1. For box sizes up to 2000 m, fractal dimensions increased to reach 1.75. Indeed, when growing up, the boxes include more and more network bifurcations and the resulting fractal dimension increases. Above 6000 m, they varied in an oscillating fashion. This remains unexplained but it seems to be a very typical feature of distribution networks. Fractal dimensions of HV and LV grids are lower when they are considered separately. This is a strongly expected result, as the combined LV and HV cover space more homogeneously than they do separately. The same kind of analysis was finally carried out on different towns in Jura and Haute-Saône to compare built-up patterns and the spatial arrangement of power grids. We identified three different types of area as shown in Fig. 3. For St Claude, Champagnole, the grid is hypertrophied in comparison with the built-up surface. On the other hand, for Lure, Luxeuil, Héricourt and Vesoul, a dense area is covered by a relatively small grid. This is the most efficient of the three types in terms of grid proportion versus built-up surface. Dole, Lons and Gray are some intermediate cases.

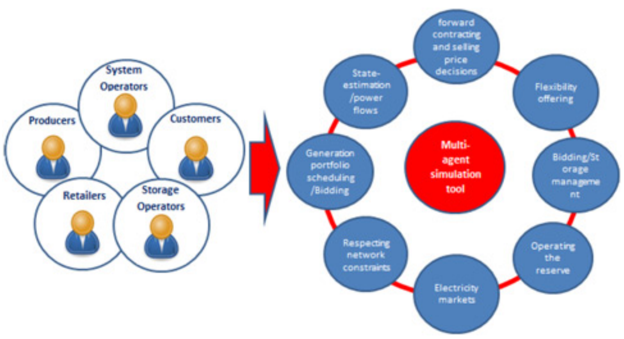


**Fig. 2** *Illustration of the multi-agent tool for the simulation of different functionalities in a multi-actor environment*

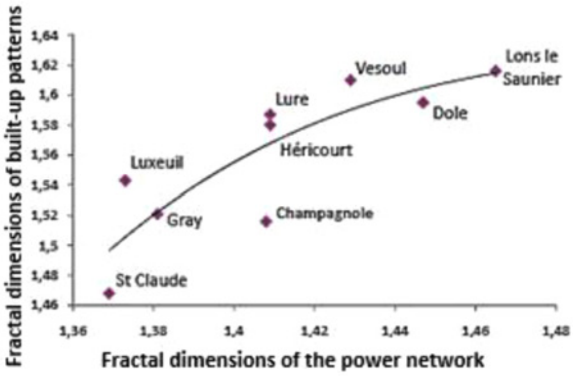


**Fig. 3** *Fractal dimensions of built-up patterns versus distribution grid for different towns*

### 4.2 Examples of considered use cases

Several Use Cases are considered in order to study alternative multi-scale organisation forms and their impact on the power system. As an example, a first use case, named 'DSO constrained control', considers a strategy in which the DSO manages system operation using a constrained control grid tariff. In a day-ahead timeframe the DSO has to guarantee safe operation of the grid. After forecasting possible constraint violation, the DSO calculates a 'grid tariff' for retailers. Then, the retailer establishes a flexibility plan that is proposed to the customer in order to reduce the number of constraints violated. Consequently, the next day, customers try to implement this plan. If constraints are violated, some load automatically disconnects from the grid and DSO charges the retailers at the Grid Tariff.

An alternative Use Case is that of an 'aggregator for load flexibility'. The DSO can operate the flexibilities offered by the different grid stakeholders in order to ensure safe operation. In this context, a local flexibility market is established. Flexibilities are offered mainly by aggregators, each of which manages a portfolio of customers. In the day-ahead timeframe, the DSO requests flexibilities by setting bids in a flexibility market and the aggregators set flexibility offers. The results of this market are the flexibilities obtained by the DSO. In real time, the aggregator implements the flexibility plan established and the DSO evaluates the technical feasibility of applying the proposed flexibility and pays the aggregator. This Use Case puts the emphasis on a new smart grid actor, i.e. the aggregator, and evaluates the possibility of establishing local markets to trade flexibilities. In this scheme, flexibility requests may also come from the TSO, while in a more general case, an aggregator may tender its available flexibilities on different markets.

## 5 Conclusions

This paper presents the state of the art, the methodology and the first results of the Fractal Grid research project. New analysis tools and design concepts based on fractal geometry are proposed to reshape smart grids and develop new smart territories in the long term. Fractal grid architectures will be established and tested on different case studies in order to evaluate the benefits of self-similarities for accessibility, flexibility and reliability. A multi-agent management strategy will also be defined to manage such an electrical system.

## 6 Acknowledgments

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