Towards complex system design and management in the engineering domain – the smart grid challenge

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Abstract

Our world is facing a significant challenge from climate change and global warming, coupled with an increased awareness about the importance of preserving the environment. This challenge calls for us to use our resources more efficiently and develop in a more sustainable way. One important part of this move towards sustainability is a radical change in the energy sector, characterized by the introduction of new technologies providing low carbon electricity generation and the use of dynamic distribution systems such as the smart grid. This shift requires the use of new tools, especially in the modelling and simulation areas. Complexity science can help us deal with the many new challenges arising, which are mainly related to a more distributed system with a large number of dynamic, interconnected resources. New approaches to deal with these issues are presented based on two case studies.

Keywords: smart grid, modelling and simulation, controllability, emergence, agent-based modelling

Our world is facing a significant challenge from climate change and global warming, coupled with an increased awareness about the importance of preserving the environment. This challenge calls for optimizing our resources and developing in a more sustainable way. One of the results of moving towards sustainability is a paradigm shift in the energy sector, characterized by the general trend of introducing new technologies and resources in a movement towards a *smart grid*. This shift requires the use of new tools, especially in the modeling and simulation areas. It has been shown in Viejo et al (2011) that complexity science could help to deal with the new challenges arising, which are mainly related to a more distributed system with large number of dynamic resources which will be more interconnected and communicating. New approaches to deal with these issues are presented based on two case studies.

Complex systems develop characteristic phenomena that seem to be common to them, even though the nature of the system might be completely different. The existence of complex network topologies within those systems, as well as phenomena such as emergence or system properties as resilience, have already been explored. These studies deal with an analytical and explorative point of view of the system. This approach is mainly derived from natural sciences where the complex system theory allows for the better

understanding of the system's behaviour. Biological systems, such as a cell which can be seen within a compound or aggregate, forming different modules like organs within an organism, are truly complex systems. Today these systems can be explored and can be better explained due to advances in complex systems theory over the last few years.

However, in an effort to apply these findings to man-made systems, the questions are rather different. Exploration might be a topic, but as the system itself was engineered by man, its fundamental mode of operation and its structure is well known. This is not the case in biology. In addition, man-made systems are conceived in pursuit of an aim. Therefore, it seems important to ask how the system works, and also how we can influence its operation in order to better fulfil the goals for which the system was created. Liu, Slotine and Barabasi (2011), introduce the term of *controllability* which aims to find the ways of influencing the behavior of complex networks. This is a step towards being able to design and manage complex systems in an efficient way.

This is especially the case for a system like the electric energy system. Its main aim is to provide a reliable and safe power supply to its final users – which should be both cost-efficient and sustainable. So far, the management was done through centralised power plants which followed the demand. However, by the introduction of large numbers of distributed resources, the system has an increased heterogeneity and the degrees of freedom get multiplied.

The electrical energy system can be mainly described by its different voltage levels. The high voltage grid is used for the transmission of energy over large distances. The distribution grid distributes electricity regionally. Finally the low voltage grid connects the final consumers locally. Historically, the flow here was unidirectional, as centralised power plants injected energy in the upper levels of the system. Nowadays, this paradigm has changed as production is possible at almost any place of the system. Especially distributed resources have entered the system, which can be fluctuating in many cases (photovoltaic or wind energy). These fluctuations can have effects over the system and through the different levels. Therefore, a trend towards a smart grid has been emerging in the last decade.

The control and management of large number of distributed resources poses new challenges, as many different strategies are possible, which take place in a constrained framework which is also characterised by a large number of actors and stakeholders. In order to design a control and management strategies for smart grids, a complex systems approach is proposed. Therefore, we have to consider the energy system as a system-of-systems. Due to the paradigm shift in the energy sector, an increase of decentralised decision processes has taken place which allows more and more distributed control strategies. Furthermore, the inclusion of communication increases the interactions between different parts of this complex system. Moreover, the heterogeneity of the system is being increased by these factors.

Current tools are often specialised on one scale or level only and have a very specific objective. There are specialised tools for analysing the transmission grid, other focus more on the distribution grid or on pure physical aspects (load flow tools, etc.). For example, it is

difficult to represent the effects of distributed generation (which injects at lower levels of the grid) on the higher system levels. There is a lack of interoperability of these tools, which inhibits representing cross-scale interactions. Furthermore, some tools considering the communication throughout the system, which was almost nonexistent before, are still in development.

For representing the different entities and subsystems, a disaggregated approach is fundamental. The behaviour of each individual entity can be modelled and represented. This further allows including the interactions among the components and trace cause and effect chains. These dependencies are important to understand emergent effects in an interconnected multi-layer system.

The penetration of distributed resources into the energy system involves different challenges. For now, the "fit and forget" practices are usually applied, where the resources are introduced based on local criteria or incentives. However, if for example, if many PV generation cells are installed in a system, they will globally affect the total load curve. A management from the local, end user's point of view might no more be a reliable solution for the system: maximising the feed-in to the grid to maximise revenues from a feed-in tariff which is a local motivation for the client, might lead to undesired effects on the system if this behaviour is pursuit by many generation units at the same time and there is not sufficient demand to absorb this production peak. Strategies to cope with these problems are therefore needed.

Not only generation is to be managed. In the past few years, demand-side-management (DSM) has been mentioned frequently to adapt the demand side to a more fluctuating production due to renewable energy sources. As the demand side is composed of a large number of heterogeneous entities, distributed control strategies can be applied. For example, appliances can be managed to consume at more favourable time slots - or shut down to reduce demand at critical situations.

Case studies for the modelling and simulation of energy systems
Multi-level island energy system modelling

In the first case study, a coupled multi-layer model is presented. The model represents an energy system as a whole, such as the island of La Reunion, which is currently being used as a smart grid test bench in the Millener project (EDF Systèmes Electriques Insulaires, « Le projet Millener, 2011). The transmission or high-voltage system is represented, by including centralised generation units as main producers, and the substations as sinks or consumers of the system. In order to represent the effects of distributed photovoltaic (PV) generation over the grid, a classical load-flow model was coupled to a spatially referenced model of the system and overlaid with cloud coverage. The distributed PV cells were represented at the substation level, and located nearby. Cloud coverage has an immediate impact on the generated power of a PV cell, as it reduces the output power directly (there is no mechanical inertia as for classical generators or even wind turbines). Therefore, already even small clouds can have considerable impacts on the PV generation.
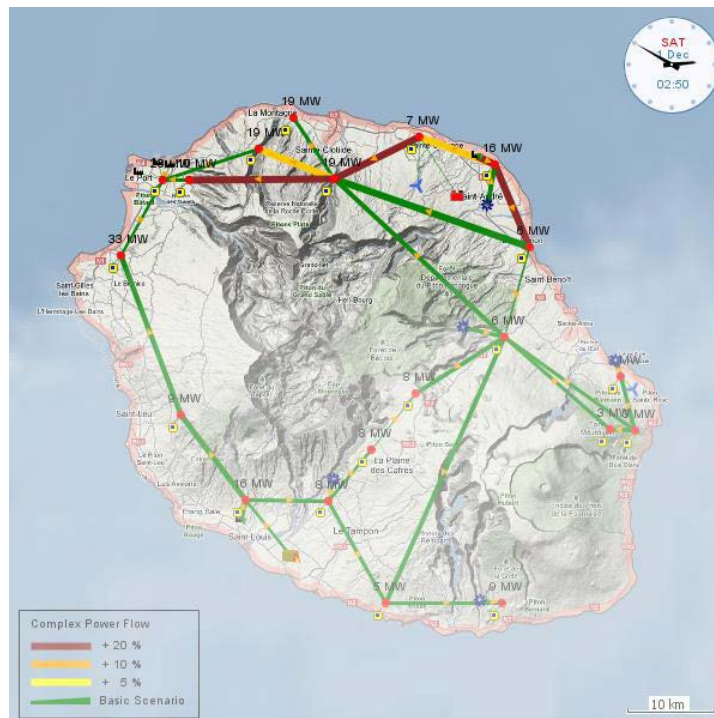
Figure 1: Map showing the cloud coverage and impact on the distributed PV installations on the energy system of the island (Höschle, H.P ,2012).

The presented model allows visualising the variation the power flows on the transmission grid in comparison to a reference scenario. This allows observing the fluctuations on the flows due to cloud cover on the PV generation sites. As can be seen in Figure 1 due to a cloud in the southern part of the island, an increase of the flows in the north, where most of the centralised production is located, can be observed.

Emergent phenomena of a decentralised demand-side management system

The second case study concerns the distributed management of refrigerator loads for supporting frequency stability on island grids. There are even newer studies which do not lead to such promising conclusions, however on a small island system like La Reunion we checked with our experts from the utility that this definitely would make sense. Grid frequency, which is almost homogeneous over an electric system (synchronised system), can be seen as an indicator for the balance of generation and demand. An over-consumption without a corresponding increase in production will lead to increase the load of the system, which will reduce the synchronisation speed of generators. This is equal to a frequency drop.

Generation is controlled by the so called primary reserve on the production side, which adjusts automatically the generators to achieve a balanced system. However, in island systems which show less resilience than large interconnected grids, frequency issues are common because individual production unit failures are relatively large versus the total capacity of the system. Therefore, a support of the primary reserve by acting on the demand side was tested in a simulated environment (Kremers, E., J. M. González de Durana, 2012).

Refrigerator loads work in a cyclic mode, due to the cooling phase in which the compressor is turned on and consuming electrical power, and a heating up phase while the temperature of the refrigerator increases - until the compressor is turned on again. By disconnecting a refrigerator we can shed its load (if it is working) or avoid it turning on. In this example, the refrigerators are controlled by the grid frequency and will be disconnected if this frequency drops too quickly which usually indicates some production failure. Likewise, they will be reconnected if the frequency reaches a threshold value again.

An emergent phenomenon observed in some of the simulations in which, an under-frequency load shedding (UFLS) was applied. With this simple UFLS strategy, a rebound effect was observed, which can lead to synchronisation of the working cycles among different refrigerators, which individually have a pulsing load curve. The synchronisation of a large number of them can have fatal effects on the system, as an oscillation of loads and frequency was detected (Kremers, E., J. M. González de Durana, 2012).
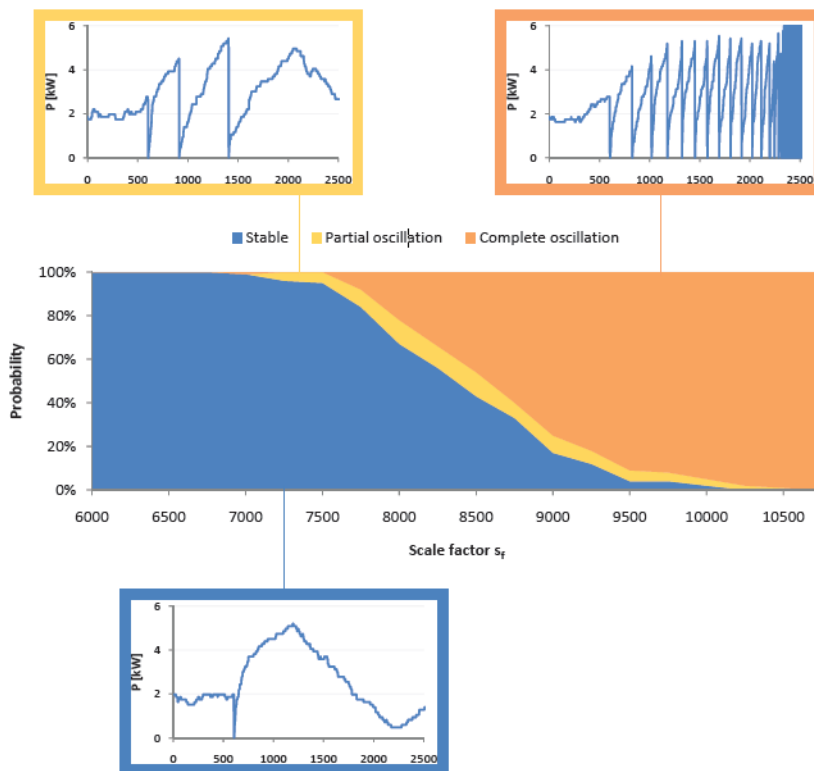

Figure 2: Phase transition from a stable to an oscillating regime on a frequency based load shedding system for refrigerators. The higher the scale factor (ratio between simulated loads: extrapolated loads), which determines the amount of controllable refrigerator versus the nominal system load, the more probable it is that the system oscillates. Results are computed through a Monte Carlo simulation with 100 runs for each value of s_f. The small plots show one exemplary simulation for power [kW] against time [s] for each regime.

Three regimes where identified which characterise the system as stable, partially stable and oscillating. This phase transition from a stable towards an oscillating system has shown many parallels with synchronisation effects that have been thoroughly studied in complexity science, such as hands clapping or firefly lightning (Winfree, A.T., 1967). The

model allowed us to understand and analyse the origins of this phenomena. This was possible through the exploration of the individual behaviour of the agents, as well as by using statistical methods such as Monte-Carlo simulations to analyse the behaviour of this non-deterministic model over several cases.

Conclusions and outlook

Both examples show the importance of the management of distributed systems, and the need for the development of intelligent local strategies to ensure the sustainability of the system. The models showed that emergent phenomena which are not captured by classical models can appear on the system, such as synchronisation of loads which leads to unwanted oscillations of the system, which could not be directly inherited from the individual control strategies. Therefore, approaches used in complexity science can be useful to represent such effects on the system level. Agent-based modelling and other individual-based modelling techniques can help to better understand behaviour of the system. This step is fundamental to the development of management strategies, which take into account that the energy system is complex and capable of emergent self-organization. The system requires new methodologies and approaches, which take into account different levels and scales and consider the interactions and effects that take place across different system levels. In this way emergent phenomena such as undesirable load flow increases or synchronisation effects can be well understood and subsequently correctly managed to maintain the system within a desired trajectory.

Even though controllability of complex systems is still in an early stage, many of the findings related to emergence and systemic behaviour of complex systems in other domains, such as sociology or biology can help to provide further elements for the application to man-made technical systems. Based on the discussed examples this has been shown by using multi-scale models including cross-scale interactions and different aspects of the energy system (electrical, meteorological, etc.).

References

EDF Systèmes Electriques Insulaires, « Le projet Millener », http://sei.edf.com/actualites/le-projet-millener/pourquoi-millener-y-83904.html

Höschle, H.P. Agent-Based Modelling and Simulation of the Energy System on La Réunion - Impact Study for Distributed PV Installations. Diploma Thesis. Karlsruhe Institute for Technology, Institute for Industrial Production (IIP), 2012. Karlsruhe, Germany.

Kremers, E., J. M. González de Durana, et al. Emergent synchronisation properties of a refrigerator demand side management system. Applied Energy, 2012. http://dx.doi.org/10.1016/j.apenergy.2012.07.021

Liu, Y.-Y., J.-J. Slotine, and A.-L. Barabasi, Controllability of complex networks. Nature, 2011. 473(7346): p. 167-173.

Viejo, P., Kremers, E., Tejera, M. H., et al. "Towards an interdisciplinary approach for the simulation of future smart grid architectures from a complex systems science point of view". In European Conference on Complex Systems (ECCS). 2011. Vienna, Austria.

Winfree, A.T. Biological rhythms and the behavior of populations of coupled oscillators, J. Theor. Biol., vol. 16, no. 1, pp. 15–42, Jul. 1967.