NEW PRINCIPLES OF OPERATING ELECTRICAL DISTRIBUTION NETWORKS WITH A HIGH DEGREE OF DECENTRALIZED GENERATION

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ABSTRACT

The increasing share of decentralized small and medium power plants opens up interesting options for a paradigmatic change of network operation strategies. On the one hand fluctuating generation principally endanger robust network operation. On the other hand there is an economic and ecological pressure to maximize the infeed of renewable energy sources. There is therefore a need for a cheap and scalable solution to meet these challenges. The solution we propose requires more decision intelligence and communication between the players in the electrical network. Scalability is achieved if the central control task is distributed among the intelligent players. Optimization of the control problem then means to devise a set of roles for the players and rules among them. We present such a basic set of roles and rules. We discuss the self-organization that occurs on the basis of these rules, the system performance as well as the consequences for the evolution of present-day strategies of network operation.

INTRODUCTION

Since many decades power distribution grids are designed from the bottom to the top, which means from low voltage to medium voltage networks based on principle structures like open rings and radial feeders. The target of those networks is the distribution of electrical energy from high voltage levels to the customers connected to the medium and low voltage levels. Lines and cables in these static networks are normally loaded less than 50% to guarantee (n-1) contingency and therefore distribution network operation is limited to switching actions in case of an outage only. There was no need to use any load flow control algorithms for the whole distribution networks because of the one directional load flow scenarios and the available reserve capacity of the network. Currents and voltages will only be measured in the main substations. Basis for network planning was the experience of the network operator in the past. The estimation of loads and knowledge about the supply area and future development was sufficient enough to design the distribution network for top-down load flow only. The maximum load scenario could be described precisely already in a long term planning state - many years before it will occur.

Future scenarios of electrical power supply are driven by the high impacts of new decentralized generation units on the one side and new kind of consumers on the other side. Photovoltaic (PV), heat pumps, combined heat and power plants (CHP) and electric cars are only some examples that might be integrated into the future networks and will lead to new challenges in network design and operation. These new devices will be implemented in high quantities to fulfill the requirements of the European Union to reduce CO$_2$ emission. When the grid parity of photovoltaic or other renewables will be reached in a few years a high number of dispersed generation units will be integrated into the distribution networks and force the difficulties of reverse power flow. In total the energy mix of the future will be based on central power plants as well as on dispersed generation as shown in figure 1.

![Figure 1. Smart Grid – future network scenario](image_url)

The rapid changes in electrical power supply will lead to new technologies, new network design criteria, new market players and new consumer behaviour which will be integrated into the existing system of conventional generation and power distribution.

The driving forces of a possible paradigmatic change of
power supply systems are quickly named:

foremost the awareness that fossil based energy production is the most likely cause of the presently observed climate change,

secondly the fact that alternatives of electricity production have become technologically mature and economically attractive and

thirdly and often forgotten the “new ideas effect”, that a new generation wants to do things a little different from the old generation.

These driving forces have the potential to completely alter the technological realization of electricity generation. But increasing dispersed power generation does not only mean a change of generation technology but also a change in the power system structure. In this understanding dispersed generation means generation close to consumption. In parallel to dispersed generation, generations from renewable energy can also be done in large central power plants (e.g. wind parks, concentrated solar power plants). The exact ratio of central to dispersed power generation than depends on regional and infrastructural factors.

Yet the increased fraction of dispersed generation will also mean a substantial increase of the sheer number of generators connected to the system. This number may well increase by many orders of magnitude. This is a change of the structure of the system that will cause an enormous organisational problem. Analyzing this problem soon reveals that it is not only a technological problem but also a socio-economic problem. It is therefore obvious to look for solutions to this problem not only in the technical sciences but to involve social and economic sciences as well. If we raise the question of how to organize large assemblies of actors we immediately see the parallelism to the historical approaches of how to organize societies. The large “bi-polar” debate in the 20th century was among the socialistic/centralistic forms of society and the capitalistic/market-based structuring of societies. Apart from the ideological aspects of this debate the work of Friedrich August von Hayek [1] has opened the awareness of the information theoretical aspects of these alternatives. According to Hayek the efficiency and robustness of a societal system is dependent on the amount of information and information processing contained in the system. By its mere definition a centralized system will always have less information than a system with decentral control. There is always the problem of keeping the information flow to the central control actual and to provide a calculational power at the center that is sufficiently large. Hayek coined the term “pretence of information” and expresses that the central approach always fails to meet this challenge. Translated into the technology of network operation we immediately see these problems in the reality of SCADA (supervisory control and data acquisition) systems. The designs of these systems are rooted in an era where wide area information networks were a proprietary ingredient of separated applications like telephony or energy supply.

Through the Internet this situation has completely changed and wide area information exchange has become a public resource. The pretence of information has therefore lost its basis. The paradigmatic change that can happen here is that the operation of electricity networks will be mapped on the new concepts of information exchange that have developed through the Internet. These concepts are “web services”, “description/mark-up languages”, “Client-Server relations”, “Peer to Peer communication”, “Package oriented information flow”, “Players, Roles and Rules”, etc. What we will undertake here is to formulate a minimal set of players, their roles and the rules with an Internet “flavour” in mind indicating the path from concept to implementation.

**ROLES AND RULES**

**The Trade Act**

We found that the fundamental ingredient of the societal self-organization is the trade act that underlies every energetic interaction. Taking this concept very seriously it means that each switching on and off of a light bulb has to be associated with a contractual act between consumer and producer. This fundamental axiom has to meet the practical requirement that the contractual interactions between supply and demand side have to be automatized and simplified as much as possible. Even though this automatisation and simplification may lead to similar structures as today, i.e. comprising bundled contracts, load-forecasting, etc. it is important to note that the strict realization of this basic feature has far reaching consequences for the whole philosophy of the system construction applying to all aspects from technical control to the economical questions involved. For the technical control it means that we reach a “No-Surprise-Scenario”. There is no regular load or generation change that is not announced and therefore accounted for by a positive or negative balancing energy that is already in “stand by”. Thereby system failures which are not caused by hazards but by generation-load imbalances can principally not happen.

**Table 1. Building Blocks of a Service oriented Architecture of energy network operation**

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<tr>
<th>#</th>
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<tbody>
<tr>
<td>1</td>
<td>PEA - The Private Energy Agent</td>
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<tr>
<td>2</td>
<td>LEX - Local Electricity Exchange Market</td>
</tr>
<tr>
<td>3</td>
<td>EP - Electricity Police</td>
</tr>
<tr>
<td>4</td>
<td>IA - Island Administration</td>
</tr>
<tr>
<td>5</td>
<td>NTA – Network Transport Agent</td>
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</tbody>
</table>

From this basic axiom we formulate the following players their roles and the rules of interaction among them. Table 1 lists the 5 essential players and figure 2 depicts the relations among them. We describe their characteristics starting with...
the PEA – Private Energy Agent.

**The Private Energy Agent**

An instance is needed that is operated by every energy producer and consumer which to a high degree can act autonomously. We call this device the *Private Energy Agent*. Most prominent is its function to communicate via the Internet with other PEAs. It represents its associated energy production or consumption device towards the public. It combines economical and technical aspects by closing energy contracts with other PEAs as well as ensuring that the power devices connected to it will meet the requirements from the contract. It has to implement the major functionalities listed in table 2.

**Table 2.** Major functions of PEA (Personal Energy Agent)

<table>
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<th>#</th>
<th>Function class</th>
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<tbody>
<tr>
<td>1</td>
<td>External communication</td>
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<tr>
<td>2</td>
<td>Financial functions</td>
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<tr>
<td>3</td>
<td>Control of power flow</td>
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<tr>
<td>4</td>
<td>Measurement functions</td>
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<tr>
<td>5</td>
<td>User-Interface functions</td>
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<tr>
<td>6</td>
<td>Reporting functions</td>
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**The Local Electricity Exchange**

The determination of the electricity price can be done bilaterally between two PEAs, but in many cases matters will be simplified if producers and consumers can meet on an electronic market. According to the principle of decentralization of information electricity markets can also be realized locally which is why we termed this role LEX – Local Electricity Exchange. Besides its local functions of measuring and controlling local demand and supply the PEA has to become active on an outside market in order to sell and buy energy. The LEX exists as a web-server and is accessed by the PEA’s via standardised protocols. The important functions of a LEX are: Collection of offers and demands, Calculation of market clearing price, Realization of contracts, Presentation of trading activity on a Web-Page, Contacting other and larger LEXs in order to satisfy over- and under-supply, Reporting to suppliers and consumers.

**The Network Transport Agent**

The aggregated offers and demands can not be necessarily realized. Before LEX computes the “market clearing” it sends the aggregated bids to the NTA. The NTA conducts a power flow calculation and by this determines which trades can be realized. Different policies for the decision making are possible at the NTA. The trades that can not be realized due to network overload may be selected by a “first come – first serve” policy or other criteria. Once the power flow calculation and decision making has been concluded, this information is sent back to the LEX which then calculates the market clearing and price. If there are trade actions between PEAs directly they equally ask the NTA for confirmation and are included in the decision making process.

**The Electricity Police**

The difference of electrical energy as a good with respect to other goods is its indistinguishability. The vendor of electricity can not put an address label on a chunk of electricity specifying unambiguously its destination. There is no intermediate instance to trace a travelling package of electricity. Instead each vendor puts the chunk of electricity that he has produced into a common pool and the consumer takes a chunk of electricity from the pool according to the certificate that he has bought. There are two basic options for fraud in this situation

- A vendor charges for energy that he has not put into the pool
- A consumer takes energy from the pool for which has not paid

There has to be a controlling institution that has the entitlement to ensure the lawfulness of the trading actions and also the executive powers to interfere in cases of fraud. This institution we want to term the “Electricity Police (EP)”. The EP can be realized as a web-server. Its basic functionalities are: Monitoring of the trading actions, Check of contract fulfilment, Conduction of measurements to trace energy shortfalls, Access right to PEA’s, Check of integrity of the seal of a PEA, Right to command a shutdown or power reduction of a producer or consumer, Executive right to force a shutdown or power reduction of a producer or consumer, Acceptance of charges of suspected fraud, Conduction of investigations.

**The Area Administration**

There is a fundamental contradiction inherent in decentralization of information in the electricity network due to the fact that to first order the electricity network is
not a network at all, but a point. The term “copper plate” is very applicable. Therefore on one hand we want to segment information but on the other there is a very strong, wide area coupling between components hooked on the network. Furthermore quantitative analyses on the basis of accurate weather data of the spatial and temporal energy production in Europe with a high share of renewable generation show that balancing the temporal fluctuations (e.g. a drop of wind energy of 80% during 5 days) of all forms of renewable energy generation can not be compensated purely locally. Therefore the system is strongly coupled on many scales. The segmentation of information that we deem necessary in view of system efficiency and scalability has therefore be accompanied by an area segmentation that leads to a contradiction with the physical and electrical reality of the network. The solution to this is that power flows in and out of certain “information areas” have to be fixed to their contractually agreed values. Thereby problems occurring in one information area are not propagated to the next. There needs to be an instance that takes this role which we call the Area Administration. Earlier we tried to establish the term Island Administration, yet this formulation often implies that the large distance energy transport is abandoned. This is a wrong conception given the enormous amount of balancing between wind and solar power generation we concluded from our weather analysis. A strong grid is in place with areas connected to it which are segmented by means of power controlling devices in order to achieve the important information segmentation. Certainly these power flows are not fixed to static values but change dynamically on a contractual basis as we have discussed above.

**CONCLUSIONS**

The consequent and enhanced usage of communication between all generation and load components in a future energy distribution network will be a strong lever and a precondition for a stable and secure network operation. It is a necessary precondition to make the network administration scalable such that given the large number of generation units envisaged in the future they can connect and disconnect to the network without a central instance controlling it. The trade act which accompanies any electrical interaction is at the heart of the design of interaction rules. The physical controllability is ensured if information segmentation is accompanied by a physical segmentation of power flows between information areas. The legality of contractual interaction has to be guaranteed by a police-like instance that has the right to monitor and compare contractual and electrical data.

**OUTLOOK**

The implementation of the scalable system requires the standardization of the information exchange between the web-services LEX, AA, EP and NTA with the Personal Energy Agents. A prototypical implementation is under way in the Siemens research department.

**REFERENCES**
