Integrated Modules for optimized operation of distribution grids

Dirk Westermann, *Senior Member, IEEE,* Michael Kratz, Mike Ifland, Steffen Schlegel, *Member, IEEE*

***Abstract*— The automation of power networks with all means that are available today – better known as “Smart Grid Approach” – has been the topic of many research activities for almost one decade. However, the degree of distribution system automation is rather low in today’s networks. The authors believe that many modules, which are designed to solve the detailed problems of each focus area, need to be embedded into one holist but even more general concept. Based on this general hierarchical approach this paper focuses on different modules that can be used at different stages of the distribution grid**

***Index Terms*— Smart Grid, Smart Meter, Optimal Power Flow, Battery Electric Vehicles**

I. INTRODUCTION

The full automation of power networks with all technical means that are available today – better known as “Smart Grid Approach” – has been the topic of many research activities for almost one decade. Even though smart grids are not limited to distribution grids, the main focus of the activities has been in the context of medium and low voltage networks. Various methods and technologies are considered today to make distribution systems more effective and to provide some sort of automated network operation, as it is known from the transmission grid for many years.

However, the degree of distribution system automation is rather low in today’s networks. An explanation for this can be found in the historic grid development. End customers had to be served with power according to their demand (principle of demand following supply) and there was simply no need for extensive measurements except the energy relevant metering. On the other side there was almost no controllable device on the distribution level. Consequently, distribution system automation was not needed at all.

With the advent of distributed generation and the actual generation of software based measurement systems at a lower cost level than those for transmission applications, an increased amount of automation became feasible and also mandatory at the same time.

As a third pillar of the distribution system automation theme, controllable loads and storages came up. In particular the latter ones are expected to have a significant load share in connection with battery electric vehicles (BEV). BEVs can be considered to provide a huge potential for grid control and might become a key component in distribution system management. In summary the following major challenges in connection with future distribution system operation have to be met:

- Fluctuating non-deterministic energy infeed, mainly caused by renewable sources.
- Availability and reasonable installation base of cutting edge of technology based measurement and control systems, even for private households (referred to as smart meters).
- Automation (remote control) of loads with storage characteristics, predominantly in private households (mainly battery electric vehicles and other storages related to domestic heating or cooling).
- Interface to and concept for embedding into energy management systems of the new degree of freedom of load control and network control on distribution level.

All the sketched problem areas cannot be solved with one single approach. The authors believe that many modules, which are designed to solve the detailed problems of each focus area, need to be embedded into one holist but even more general concept. Based on this general hierarchical approach this paper focuses on different modules that can be used at different stages of the distribution grid. The ones with highest potential to have a significant operational impact have been chosen to be presented here:

- Systematic involvement of the load control degree of freedom of end customers for grid optimization by means of smart metering and the
- active utilization of battery electric vehicles as means for demand side management.

After a general introduction into the control philosophy and the overall concept definition of “Smart Grids” this paper will present some results of real case studies. Even though many countries in the world are affected by unbundling, regulatory issues, fluctuating renewable infeed and smart grid activities, this paper will focus on the situation in Germany which can be considered as exemplary for countries with a huge amount of renewable energy infeeds.

II. SMART GRIDS

The original structure of power system control and operation was designed for integrated utilities. Which means generation, operation and grid owner were unified in one single company. Consequently a stable closed loop grid control was possible. The simplified feedback loop depends on generation and demand only. But with the ongoing unbundling and liberalization process the operation then turned into a complex system, which is influenced not only by physical constraints. The non deterministic generation from renewable resources disturbs the “classic load following” power system operation. Furthermore a loss of control is caused by the divided responsibility from transmission and distribution grid operators. Obviously the overall system stability decreases with an increase of all disturbance factors. Especially in distribution grids the amount of aforementioned disturbances is even more severe due to a lack of appropriate supervision and controllability. A well proven method for enhancing system stability is the change of transmission characteristic – better known as grid extension. Under the aspect of infrastructure efficiency this would not be a suitable solution.

Therefore the disturbing demand has to be transformed in a controllable degree of freedom. The required closed loop operation mode can be considered as the basic structure for the smart grid approach. Based on this, stabilizing the power system on distribution grid level becomes possible. Integrated modules for this smart grid approach are illustrated in figure 1.

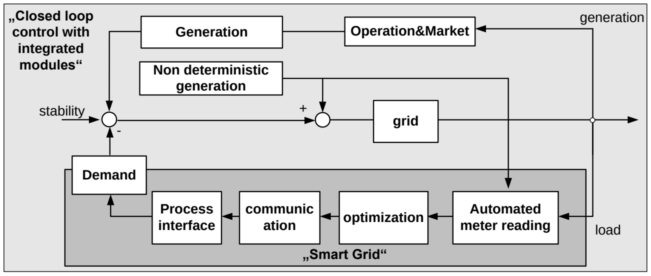

Fig. 1. Integrated modules for optimized operation of distribution grids

To describe the integrated modules and the interoperability for optimizing distribution grids is a question to be discussed in this paper. The proof of concept will be done by case studies on several pilot projects.

A. *Definition of Smart Grids*

The European and U.S. vision for Smart Grids has evolved over the past decade and has begun to achieve a next level of development. To come to a uniform understanding of the smart grid approach both visions and in fact definitions must be compared. The Smart Grid definition refers to a completely modernized electricity delivery system which monitors, protects and optimizes the operation of its interconnected elements from generation over distribution down to demand. Smart Grids include central and dispersed generation in high voltage transmission networks and medium & low voltage distribution networks [1].Today’s gap of energy storage harmonizing fluctuating infeed and demand might be closed by utilizing energy storage systems in electric vehicles, end-user incorporation by smart metering or residential building automation systems. Smart Grids are characterized by a two-way flow of electricity and information. The benefits of a distributed communication and computing power to deliver information about power supply and demand in real time are incorporated as well. [2]

Smart Grid is a terminology which was originally proposed in connection with the establishment of a European Technology Platform [3] in 2006:

> *“A Smart Grid is an electricity network that can intelligently integrate the action of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.”*

According to the Smart Grids vision, electricity networks must comprise the following properties:

1. **Flexible** – fulfilling powers system stability responding to the technical changes and self adoption and operation opportunities
2. **Accessible** – granting connection access to all network participants
3. **Reliable** – assuring and improving security and quality of supply, consistent with the demands of the digital age.
4. **Economic** – providing best value through innovation, efficient energy management and ‘level playing field’ competition and regulation.
5. **Sustainable** – particularly for renewable power sources and high efficiency local generation for minimizing carbon emissions

B. *Non technical constraints*

There are several external parameters, which tend to interfere with the smart grid approach. With energy market liberalization in Germany, integrated utilities lost their right of existence and had to be divided into single, autonomously operating branches. Thus in an unbundled utility environment an integrated operation of all power system components as it is suggested by the smart grid approach, is clearly impossible. Marketing and grid operation do not go hand in hand anymore. Furthermore, the metering access regulation in Germany stated, that customers can choose their metering provider independently from the energy supplier. Consequently, grid operators cannot use measured data gathered by smart meters in private households. Finally, the German market regulator *Bundesnetzagentur* installed an incentive based regulation to simulate business competition in grid operation. Due to the sudden investment climate´s deterioration, system operators in Germany and other countries with similar regulations have to sharply calculate, whether investments are approved and turn out to be profitable or not.

III. MODULES

A. *Non-deterministic generation*

Due to the increase of renewable energy infeed in countries all over the world power systems have to meet the challenge, of uncontrollable, decentralized generation. From the system operation perspective wind power generation appears to have the same behavior as expected from a negative demand. In fact the forecasting of wind power infeed is not as reliable as classic load forecast due to a variable pattern. Figure 2 shows the histogram of the forecast error in relation to the control area load in a German TSO area in 2009.

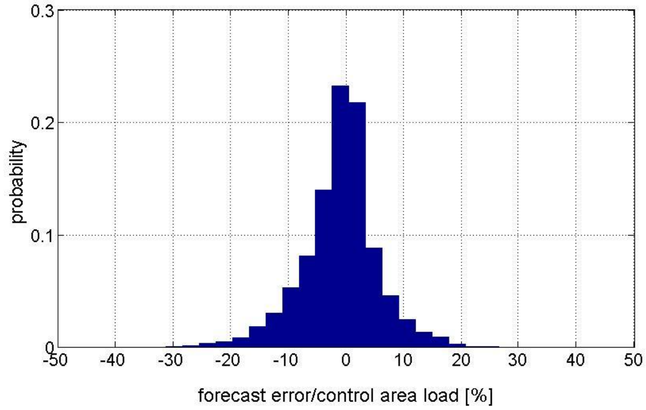

Fig. 2. Histogram of wind power forecast error relative to the control area load (median = -0.3% standard deviation=9.2%)

Subsequently, with an increase in wind generation and a steady level of demand the relative forecast error will also increase. E.g. the installed wind power in Germany currently ads up to 25.8 GW (2009) and will reach approx. 60 GW in 2020 [4]. Therefore the need of conventional generation for power system regulation will grow. Otherwise the optimization of distribution grids with the smart grid approach is expected to provide an adequate solution [5,6].

B. Automated meter reading

To gather information about a consumption process, an adequate metering method is inevitable. For the last few years, automated meter reading (AMR) has become a state of the art technology which is also known as “smart metering”. Typical measurements of AMR in private households are apparent power in a 15min value resolution. The consumption is generally accumulated over this time interval and then stored in one of several registers. The amount of registers varies from manufacture to manufacturer. The measured data currently underlies proprietary standards and forms the devices output. The output can be transmitted to the measurement provider by GPRS or Powerline Communication (PLC), which are the most frequently used transmission methods. While the devices work either in push- or pull mode, the data is transferred usually once a day to the receiving destination, usually defined by an IP-address [7].

The measurement provider then transmits the collected data to an energy data management (EDM) to allow accounting.

For the data transfer, an unspecific delay time has to be taken into account. Delays occur due to limited bandwidth and disruptions in data transmission lines. A typical disruption could be a temporary breakdown of the communication network, especially, if it is operated by a third party. Also, former case studies show, that insufficient reception in cellar buildings can cause delay times in data transmission.

AMR in smart grids allows integration of private customers in network operation by the use of flexible tariffs. But data acquired by AMR cannot be used directly for network operation, for several reasons:

First, due to the time delay mentioned above, the 15min-values would be simply out of date, when they arrive in the DSO´s management system. For reasons of cost and delay, meters are being read out only once a day.

Second, data privacy is a major issue, which cannot be neglected. With the technical opportunities of AMR devices engineers tend to forget the principles of data avoidance and data minimization. These principles state, that unless a measured variable is not absolutely essential - for accounting reasons for instance - it must not be taken. Furthermore measured data has to be made anonymous or deleted, as soon as its purpose is fulfilled.

Third – in the German energy market – the data is acquired by a specific measurement provider and then transmitted directly to the utility. Due to the unbundled characteristic of the energy sector, such data cannot be communicated between procurement and network operation, even if both sectors work within the same company, which is quite usual now, especially in smaller utilities [8].

C. Communications

Due to the growing impact of communication systems the following requirements have to be met:

- Use of standard protocols for communication,
- Interoperability for physical different communication channels (DSL, UMTS, Ethernet, etc.) for analyzing the impact of communication quality parameters to the primary process.

If standard protocols are applied any commercially available equipment can be integrated for special scenario simulation. Most modern protection devices support communication via IEC 61850. The standard for distributed measurement values, status information and operation between substation automation and network control systems today is based on TCP /IP via DNPv3 or IEC61850-5-104 (Figure 3).

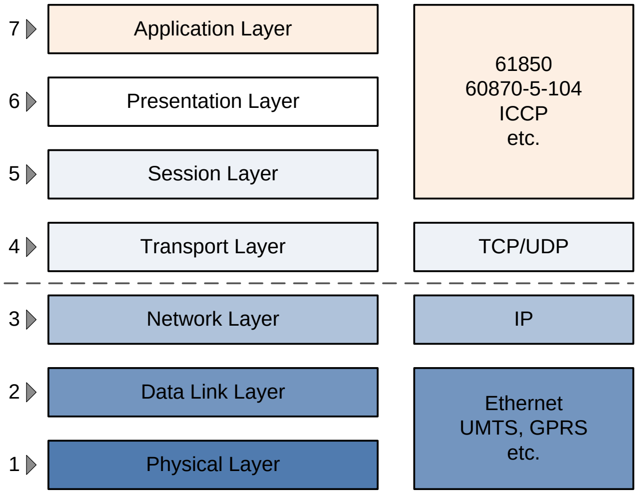

Fig. 3. ISO/OSI model / Protocols

Network control centers can be connected via ICCP (Inter Control Center Communication Protocol) based on TCP/IP. This setup becomes more and more standard. For the sake of cost effectiveness, numerous distribution utilities even let operate their distribution network from remote locations by service providers.

TCP/IP has become the standard for computer communication in today's networks. It allows standard components to build up a communication layer. The TCP/IP stack is available for the most communication systems and can be embedded into other protocols.

A change of technology in layer 1 and 2, e.g. from Ethernet to wireless or UMTS only affects the TCP/IP support. Differences are expected due to a variety of communication channels (Layer 1 and 2). These could be bandwidth, delay or package loss. Integration into the whole simulation framework allows investigation of the impact the communication system has to the operation tasks. [9, 10, 11]

D. *Process interface*

Direct and indirect options of actuating process factors have to be distinguished. In a direct process, a control system effects a remote terminal unit where an actuator takes a certain position. For various technical and regulatory reasons, this method cannot be applied to private household load control (demand side management). Thus, the main input factors for indirect demand side management interfaces would be a price signals. These signals determine, whether customers participate in the load shifting process and align their consumption behavior to the operator´s requirements. In other words, price signals determine loads in private households. Unfortunately, the reaction of a number of private households – here regarded as dynamic loads – is not as certain as a normal actuator´s one would be. Their specific character originates in customer behavior: understandably, private customers will only adapt parts of their daily routine to fit to the energy price level, and only as long as it is not regarded as a loss of comfort. Therefore, response times for private customers to follow prince incentives will differ depending on their possibilities and motivation. To determine response times, a statistical consumption analysis of the participants will be necessary [12, 13, 14].

E. *Optimization*

Smart Grids should utilize battery storage or battery electric vehicles to harmonize the load with fluctuating infeeds to minimize power flows from the next level power grid. The optimization approach of optimal power flow needs to be enhanced to meet storage characteristics. The classic optimal power flow (OPF) optimizes a power system´s steady state performance with respect to a given objective function, while satisfying a set of equality and inequality constraints [15]. An optimization for a single time step doesn't meet the storage requirements, because it neglects the maximum or minimum state of charge after a series of steady states. It can also be assumed, that a series of optimized steady states does not necessarily lead to the global optimum over the entire series. The trajectory of the decision to charge or discharge of storages in a Smart Grid should be derived with the same objective function and equality and inequality constraints. So the OPF approach needs to be enhanced to optimize a power system over time series of steady states, as shown in a very simple illustration in figure 4 for cost optimized charging.

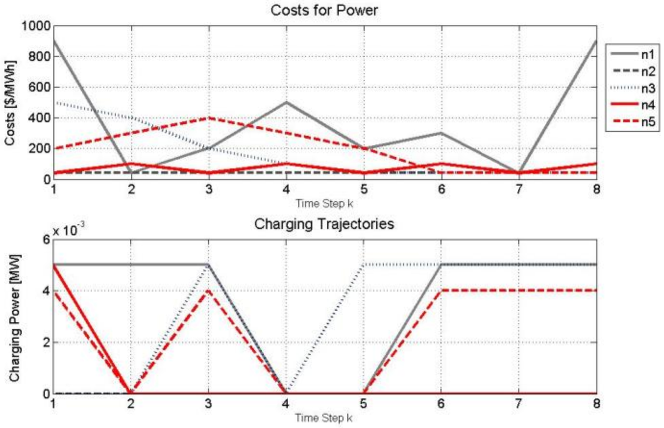

Fig. 4. Cost Optimized Charging Trajectories for a five node power system

Figure 4 shows the cost-optimal charging trajectories from an OPF. The charging slopes follow roughly to decreasing cost for power.

IV. CASE STUDIES

Due to the variety of module implementations the proof of concept could be seen best in the following case studies. They represent scientific projects the authors of the paper are working on.

A. *Domestic private end customer load control*

To integrate private consumers into grid operation, one has to consider, that private consumers cannot be shifted directly like industrial loads. In this case the operator uses three general, motivational factors to influence the consuming behavior of his customers: ecological and monetary incentives combined with detailed information about the energy consumption. First of all, private customers are willing to preserve nature by using renewable energy and improving in-house energy efficiency, which also reduces costs. With high quality weather forecasts, energy procurement can be optimized and by creating a demand, renewable energy can be used effectively. Lowering the living expenses is a second motivational factor for customers to participate in indirect load shifting. Former studies show, that the combination of both factors can lead to a significant improvement in grid operation.

The process interface can be formed by a flexible tariff, which consists of three different price steps*, covering a spread of approx.* 30% of the energy cost. Furthermore the participants can monitor their energy consumption by using a web client, which displays cost and consumption information.

Of course, one has to consider, that tariffs are only set by marketers, which – at present - do not have any reference to the actual network operating. Regarding the fact, that optimization goals in energy procurement by marketers and system management differentiate, research has to find ways, to connect these two fields of interests. The final result would be a better inclusion of customers in the process of value creation [16].

B. Remote controlled charging for battery electric vehicles

Electric Mobility is expected to provide a sustainable solution for future individual transportation. One opportunity is to synergize electric mobility and renewable energies in order to reduce the carbon dioxide footprint for every driven kilometer. The controlled charging for battery electric vehicles aims on implementing system which allows a direct a real time control of the charging load of electric vehicles. The system collects data from wind power feed, current charging power and grid load from AMRs located in distribution substations. With an implemented optimization algorithm the system schedules control signals for every participating BEV. The control signal is transmitted via GPRS as the physical communications layer to a remote terminal unit, which interprets the used logical communication layer. In Figure 5 the implemented control loop architecture can be seen. The described setup allows investigating of the general controllability of BEV-charging as well as the robustness and reliability of the used ICT-infrastructure [17].

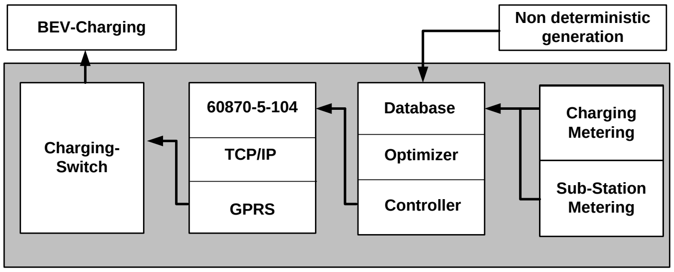

Fig. 5. Control loop for remote controlled charging

V. CONCLUSION

Smart grid is a synonym for a technology platform for universal power system automation, predominantly in medium and low voltage levels, i.e. distribution systems. There are various definitions and understandings of the smart grid idea. However, all of them converge into the above mentioned power automation view. Smart grids are enabled by state of the art information and communication technologies and focus on an drastically increased degree of grid controllability in terms of active (and reactive) power balance. This became necessary due to a shift in operation paradigms load following generation to generation following load. In this paper a definition of smart grids has been derived and two major instances of smart grid functions have been outlined and discussed. Therefore the smart grid concept has been structured in several modules for grid operation in a way that a closed loop operation with load inclusion can easily be derived. From a system engineering perspective it has been shown that it is important to derive a modularized perspective so that realization of subsets of smart grid functions can be implemented without loss of interoperability. Two major categories of smart grids have been described, namely automated meter reading and electric vehicles. Both can be considered as most promising technologies for more flexible grid operation and will serve as basis for many future research projects.

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