Future Power System Transition – step into the light

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Abstract—The transition from a centrally-based electric power system to an “internet-like” network that is able to accommodate a high share of distributed and intermittent generation, will need quite some changes at the technical level as well as on the governance structure and business level. This paper, which expresses the common vision of ECN and KEMA on the issue, attempts to categorize the problems that might arise in the current system as well as the key technologies, markets and regulatory issues to be developed. This leads to insights in what actions are needed in the short and medium term with regard to R&D, market developments and governance to take the first steps in the transition process to a sustainable future power system.

Index Terms—Future Power Systems; Transition; Distributed Generation; Intelligent Control; Demand Response; Electricity Storage.

I. INTRODUCTION

The modern electrical power system is a large sophisticated technological entity with a long history. That history stretches from a time when electricity was a minor energy source to the present day, when electric power provides many of our everyday energy needs. This migration towards a larger share of electricity of our energy consumption will continue. Nearly all forecasters foresee society making increasingly use of this least tangible yet most convenient energy carrier in the future. The existing power system has grown organically. Each new development in society was accompanied by its own incremental modification to the network, with the most obvious features of change being the continuous increase in scale and interconnection for increased reliability. Until the 1990s, nearly all the power, supplying the transmission network, came from central generating capacity, as indicated in Fig. 1. From the transmission network, the power was fed to the distribution networks that supplied the customers. Thus the power system is, in organizational terms, like a pyramid with the control centers at the top.

Fig. 1. Existing power system.

Energy carrier and generation networks will be operated different in the future. Distributed Energy Resources (DER), including e.g. wind, solar, biomass and gas-based microtechnologies are expected to supply at least 15% of all electricity requirements in 2010 in the European Union. Small to medium sized (100 kW – 50 MW) conversion technologies, including high speed micro and mini power turbines, reciprocal machines, fuel cells, power electronics, and energy storage, will be the main energy supply and conversion technologies installed on electrical network over the next years. Their share will continue to increase in the decades after 2010. This gives a vision that a future power system might look like the one depicted in Fig. 2, accommodating different technologies and a wide range of sizes of Distributed Generation (DG).
II. THE LIMITS OF THE CURRENT SYSTEM

Already today distributed generation and renewable energy sources are part of the power system. They have been connected to the network, but do not take part in power system management. This 'fit and forget' policy has been possible as long as the share of these sources was low. However, if this 'fit and forget' policy is maintained in the future, the electricity power system will become increasingly more difficult to manage, with high associated costs and inefficiencies.

A. Power exchange layer: Camel or dromedary?

A key question to consider for the future is how will the power exchange layer develop between the still existing large-scale generation, including large-scale offshore wind power, and the numerous distributed resources. Two models that can be examined are the camel and the dromedary model, which are illustrated in Fig. 3. The Camel model envisages large power plants connected to one another via a high-voltage network, while a low-voltage network interconnects the micro and mini grids that are more-or-less self-supported. Power is exchanged between the high (HV) and low voltage (LV) layer over a relatively lightweight medium-voltage (MV) network. Alternatively, the dromedary model assumes that both the large-scale plants and the micro networks are connected to each other via a well-developed and strong medium-voltage network.

Even in a strong MV network maintaining the voltage profiles within the tolerance and assure PQ with a lot of small scale embedded generators will become increasingly difficult. With only direct control functionality at the entrance point of the feeders, it is therefore likely that there will again be a demand for intelligence (power electronics) being introduced at the individual connected generators.

As illustrated, the power exchange layer has an impact on how the main issues in future networks (discussed later) will be handled and in both cases, for different reasons, calls for more intelligence in the power system. Recent studies [1], [2], [3] suggest that ultimately the camel model will prevail.

B. Categorization of the main challenges

The many problems will be related to three issues: imbalance between demand and supply, power quality and the high number (millions instead of hundreds) of feed-in points in electric power systems.

1) Imbalance between Demand and Supply

In the current system demand and supply are matched by constantly adapting supply of electricity to the demand. In a system with a large share of distributed generation and renewable energy resources, also supply will vary considerably. Without involving these resources and/or demand in the management of the system, this will lead to several problems that can only be solved with considerable costs. For instance, the price volatility at power markets will increase. This will lead to higher investment risks meaning that investors will require higher return of investment rates, leading to higher integral production costs of electricity. Furthermore, at all levels of the grid, but especially in the 'camel-model' where intermittent production takes place at the HV-level (wind offshore) and the LV-level (solar PV, micro-CHP and small wind), electricity flows will peak more often, avoided when possible). When looking at the LV network substantial investments are done locally (probably at the customers site) to balance between local demand and supply as much as possible, maintain voltage levels within tolerances and control the Power Quality (PQ) at the connection points. Because maintaining the voltage levels and control the PQ is a difficult task in the LV network with a weak MV coupling there will probably be a large emphasis on information technology and control systems.

When the dromedary model becomes reality, the MV network will be reinforced and serves as a primary means for keeping the voltage levels of the feeders within limits and maintain a certain PQ (this resembles most closely the present network situation). As a consequence limited special measures need to be taken at the local LV generators. The network companies install advanced measuring and control tools at the feeders and the MV substation transformers, cables and switchgear is upgraded and expanded to make a “strong network”.

If the camel model becomes reality, with a relatively weak MV interconnection layer, the investments are done mainly in the HV and LV network (MV network investments are
and this in two directions. This means that additional investments in the grid are necessary. Last but not least, additional reserve capacity will be needed, since intermittent supply will not always be available when demand peaks. Calculations for the UK case [4], [5] indicate that the additional annual cost for 20% share of intermittent renewables are about 600 million Euro which increases to 1,4 billion Euro at a 30% share.

2) Power Quality Issues

Both the network company and the customer determine Power Quality at the connection point as shown in Fig. 4.

The performance is determined by the nature of the public grid, e.g. “strong” versus “weak” and the installed network components that are affecting the PQ of all customers connected to that particular part of the network. On the other hand individual customers may “pollute” their own site with installed equipment like inverters and also their neighbors through the public grid [6]. It is evident that power quality is a shared public and private responsibility and to solve this, a complex investment decision problem arises: what should be done public – to the benefit of all – and what private for the customer with his specific PQ needs. Also a complex control problem emerges to safeguard the PQ at the connection point the control system must have access to both public grid information and its installed components as well as information and installed equipment at the customer site.

3) The Amount of Active Feed-In Points

As indicated above, the inclusion of distributed resources and demand as active connection points in the management of the grid, will be needed for an efficient power system with a high share of distributed generation and renewables. This means that instead of several tens of power stations that take part in the management of a typical national power system, we talk about millions of active connection points. It is hard to imagine how this can be incorporated in the current Supervisory Control And Data Acquisition (SCADA) systems that are used today. The SCADA system will at least have to be supplemented by a more distributed control mechanism.

III. KEY TECHNOLOGIES

Now that the problems and challenges are clear, we can focus on what functionalities key technologies for the future power system need to offer. The functionalities are illustrated in Fig. 5. Demand and supply need to become more flexible, and their operation should be optimized, taking into account possible electricity storage in the system and advanced power electronics, with intelligent control technology.

![Fig. 5. Key technologies for the future power system.](image)

A. Flexible Demand and Supply

Flexibility in demand can be reached in several ways. First of all there is hidden energy storage potential in houses, buildings and devices, which is reflected in the 'band' around set points of temperatures. Most control equipment still works with an "on-off" concept at the extreme temperature points (e.g. in refrigerators and inner-building temperatures). Intelligent and modulating control can help to tap this potential for flexible demand. Another unused resource of flexibility in demand is the possibility to shift processes in time without compromising the service delivered. Examples are washing and drying processes. With flexible tariffs (as used today in France and tried out in California), consumers can also be stimulated to change their electricity demand pattern e.g. for peak-shaving purposes.

Furthermore, flexibility of demand (e.g. heat pumps) and supply (e.g. micro-CHP or wind) can be enhanced by integration of thermal or electric storage in buildings, installations and devices.

At this moment it is still difficult for small production devices to participate directly in electricity markets. If small production is aggregated in larger Virtual Power Plants by using available information and communication technology (ICT), this problem can be overcome.

B. Electricity Storage

Technologies for electricity storage on small, medium and large scale are available and still improving in terms of achievements and declining costs. Examples are lithium-ion batteries, fly wheels, super capacitors, redox-flow batteries and sodium-sulfur batteries. At this moment storage systems cannot compete yet in the current electricity markets based on energy (kWh) alone. Partly this is due to high investment costs and restricted calendar and cycle life. However, there is also a value of electricity storage for reduction of peak loads.
on connection points. For example the power used in a microwave to heat a meal could be 1 kW and the energy needed might be only the content of 8 to 10 AA batteries. This capacity value of storage is, as yet, not properly expressed in power markets. With declining costs and improved market conditions the competitive edge of electricity storage will improve in the future.

C. Advanced Power Electronics

The rapid development of power electronics is a promising development [7], [8]. Components will become cheaper over time and the power ratings are steadily increasing. As a consequence of these developments it is likely that new micro, mini and small CHP as well as small wind turbines will be equipped with power electronic inverters. Small and large fuel cell systems and storage systems (battery and/or flywheel), as well as large wind turbines (direct drives) will be developed. Power electronics will serve more and more as the preferred way to integrate DER to the network [9].

Apart from using the advanced power electronics in combination with information and communication to control and manage individual generators and their connection to the network, advanced power electronics is used in combination with market models to automatically match local supply and demand. E.g. using the concept of a virtual power plant. Increase the reliability for the system as a whole by making use of active power flow steering capabilities and re-routing in case of emergencies thus creating a more robust and reliable network.

D. Intelligent Control

The current SCADA system will need to be supplemented by a more distributed way of control that is able to handle millions of active grid-connection points. Use of advanced ICT solutions is to be expected. The electricity power system will make use of the increasing degree of communication connectivity in society. In recent years ADSL and broadband connections have become commonplace, and this will increase. If we look at what ICT has to offer from the software side, two technologies stand out: multi-agent systems and automatic trading platforms. Both will be used, where possible in combination with each other. An example of a concept making use of both is the PowerMatcher, which is described in [10].

IV. MARKETS AND GOVERNANCE STRUCTURE

For a successful transition to a future sustainable energy system all the relevant actors i.e. government, consumers, network companies, generators and traders must be involved. There is a strong need for experiments, not only in the technical sense but also on the markets and organizational level. Information exchange between those levels is crucial to bridge the gaps, prevent distortion and delay and to make an integral approach possible. This is shown in Fig. 6. As markets define the success of the key technologies needed, and markets are pre-conditioned by the governance structure and related regulation, a dynamic interaction between the three levels is needed. A question that for instance should be addressed (and experimented with) is the issue “what should be done public and what private”.

A. Markets

The value of Renewable Energy Sources (RES) and DG for society should be expressed in real financial rewards [11]. Within a liberalized framework this will happen in markets. Currently the power market is mainly an energy market (in terms of kWh). Already a lot can be done to improve the integration of RES and DG: better production forecasting tools is one issue, another one is that clusters of intermittent and controllable production (e.g. wind and gas) can be formed by linking them together by an ICT network in one commercial unit that operates on the power market. For the integration of demand in the grid, tariffs based on real-time prices would be an essential step forward. This presumes of course that intelligent and distant metering is introduced.

Markets for energy (kWh’s) alone will however not solve the problems with regard to grid investment costs. It might be possible to postpone or defer grid investments if distributed generation can be used to shave local peak demands. The creation of a real-time 'capacity market' (kW) on several grid levels will be needed.

A third market that needs to be created is a market for ancillary services for power quality like voltage control. Uncontrolled distributed generation might make PQ worse, however, when it is activated at the right time at the right place, it can even help to improve. Specific incentives to do so are currently lacking. In the future such a market will be needed.

Last but not least, those DG resources that deliver most benefits to society, e.g. in terms of reducing the stress on the environment should be preferred. Providing a reward in the form of CO₂-credits and green certificates can do this.

B. Governance and Regulation

The focus of regulation today is on “how to manage the current system most efficiently”. An innovative (dynamic)
element should be added: “how to prepare for the needs for the system of the future”. Most EU Member States have not come to this point yet, which inhibits real innovation in the power system to a large extent. Regulatory regimes should be revised on a regular basis, based on new knowledge about how regulations work and can be improved to provide the right ground for the innovations needed. To do this requires space for ‘regulatory experimentation’ as e.g. is proposed in the Regulatory Power Zones concept in the UK.

V. MANAGING THE TRANSITION - STEP INTO THE LIGHT

How to reach the desired situation of a robust, flexible, sustainable and economic efficient network of the future? This question can only be addressed as a transition process [12], [13]. We have sketched some directions and ideas, but we will have to find out most of the details as we go along the way. What is sure is that the changes are not only technological solutions within the realm of the physics of the network but also in governance and markets including the information exchange and control functions between the different layers. This asks for really new integrated modeling, learning and analyzing tools with extended functionality not separated system, market or socio-economic studies. Fig. 7 gives and impression of a business simulation developed at KEMA that links technology, regulation, policy and human behavior covering all three levels in the power system.

![Fig. 7. Impression of the KEMA business simulation FleXnet.](image)

It also means safeguarding the integrity of the system as a whole by developing new integral, and distributed testing and certification methods. This in addition to the present existing separated testing and certification of hardware and software functionality of individual components. Most and above all, it means room for experimentation in technology, markets and regulation in parallel. By developing and employing above-mentioned directions the future power system can really step out of its own shadow (conservative and slow-moving) into the light, and accomplish a paradigm shift and become the true backbone of a sustainable energy system, fostering further economic growth through knowledge development and innovations.

VI. REFERENCES

VII. BIOGRAPHIES

**Gerrit Jan Schaeffer** got an undergraduate degree in Business Studies (1987) and Technical Physics (1988) at the University of Twente. In 1993 he graduated in Philosophy of Science, Technology and Society at the same university. Working at ECN from 1994, he undertook research in Technology Studies, using the history of fuel cells as a case study for technology development, which resulted in a PhD.-degree in 1998. From 1998 to 2001 he was a senior researcher at the Policy Studies unit of ECN, with a focus on renewable energy policies in liberalized markets, long-term energy modeling and learning curve theory. In 2001 he became Manager of the Transition and Innovation Group of ECN Policy Studies. In 2003 he migrated to the unit Sustainable Energy in the Built Environment as a Group Manager and Program Manager of projects focused on the integration of distributed generation.

During his career at ECN he has managed several national and European projects, has chaired sessions and conferences and published numerous papers and ECN reports on a wide range of energy-related issues. Within ECN he is currently defining a research program on Advanced Electricity Grids, with a special focus on the use of ICT for matching of supply and demand, Virtual Power Plants, intelligent electronic converters, barriers in policy and markets, and battery system research.

**Peter Vaessen** studied electrical power engineering and graduated from Eindhoven Technical University in 1985, the same year that he joined KEMA. He held several research positions in the field of large power transformers and measurements in high-voltage networks. From 1991 to 1996, he managed several realization projects, among them construction of the Dutch 400 kV substations at Meeden and Eemshaven. As a consultant he has experience in the conceptual design of integrated electrical systems and innovative techniques and tools for transforming existing large-scale hierarchical systems into flexible dynamic structures, allowing economic utilization, competition and integration of RES and DG. He is actively involved in the technology strategy of KEMA and works for the Dutch Ministry of Economic Affairs on setting up scientific research programs in the areas of power electronics and the future long-term reliability of the Dutch electricity network.

Peter Vaessen has successfully chaired and participated in (inter)national panel sessions and conferences, delivered numerous presentations and published some 30 papers. He is co-author of the Dutch book “Rapid current, the next revolution in electricity.” He has coached some 60 students (University and Polytechnic) during their practical work at KEMA.