Smart grid functionality for the high-voltage transmission grid: On the market readiness of Digital Substation 2.0 technology

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***Abstract*—The energy challenges the world is facing will fundamentally change the electricity supply infrastructure. The basic architecture of the primary grids has been developed to meet the needs of large and predominantly carbon-based or nuclear generation technologies. The transition towards a more sustainable electricity supply requires a flexible and smarter power infrastructure, prepared to cope with the massive growth of renewable generation and the correlated higher complexity and dynamics. As most smart grid initiatives today only cover the low and medium voltage levels, the present contribution highlights the technological advancements taking place in the field of high voltage transmission. The described Digital Substation 2.0 concept represents a smart grid enabling technology necessary for a power infrastructure based on bulk renewable infeed.**

***Index Terms*—Smart grid, high voltage transmission, digital substation, wide area monitoring, automated grid control**

I. Introduction

GRID-integrated renewable generation mainly by wind and solar affects the operational characteristics of the existing power infrastructure because of the stochastic nature of the sources. With an increasing share of fluctuating renewable infeed, the dynamics and complexities in operating the electric power supply infrastructure continuously rise. In countries with high renewable infeed, a shift from downstream power delivery to bi-directional load flows can be detected. To cope with the enhanced requirements and to enable real-time high-resolution information flow, next-generation energy networks based on innovative digital infrastructure are necessary.

II. Energy System Transition: The Way towards a Smart Energy Infrastructure

The fundamental architecture of the primary power grids has been developed to meet the needs of large centralized and predominantly carbon-based or nuclear technologies [1-6]. The European Network of Transmission System Operators for Electricity recently outlined that renewable energy systems will continue to be the major driver for grid development until 2030. Projects of pan-European significance will enable climate-friendly generation and help to avoid 30 to 100 TWh of renewable energy spillage (which corresponds to the annual electricity production at Three Gorges in China) [7].

Today, energy systems undergo a dramatic change: from monopoly power supply to deregulated markets and from downstream power delivery to smart distribution. Two-way flow of electricity and information between power network and consumers becomes a reality. The final goal is to achieve a zero-carbon energy system.

The transition towards a competitive and sustainable electricity supply infrastructure requires a more flexible and smarter power network allowing a greater scope for demand participation, storage facilities and other flexibility options.

The first official definition of "Smart Grid" was provided by the Energy Independence and Security Act of 2007, approved by the US Congress in the same year [8]. The term is used today mainly as a marketing term, rather than a technical definition. The European Regulators Group for Electricity and Gas stated that a fully-functioning smart grid will exploit communication networks to "cost-efficiently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety." A corresponding conceptual model is shown in Fig. 1.

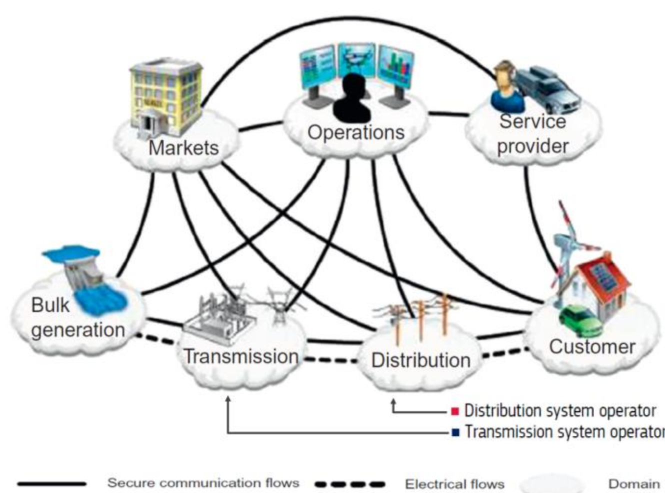

Fig. 1. The concept of smart grid: Digital Substation technology ensures smart grid functionality on the high voltage transmission level [9, adapted]

Smart grid comprises the comprehensive modernization of the electrical power infrastructure consisting in the integration of various technologies, such as decentralized renewable generation, next-generation communication systems and grid-scale storage to deliver sustainable, economic and secure electricity. As outlined in detail in [10], smart grids allow the increasing penetration of renewable resources and the participation of consumers in the network operation, help to decrease the transmission and distribution losses and subsequently to lower the energy cost for customers.

Since 2003, globally 459 national and multi-national smart grid research, development and demonstration (RD&D) projects, with a total volume of €3.15 bn are in place (Fig. 2).

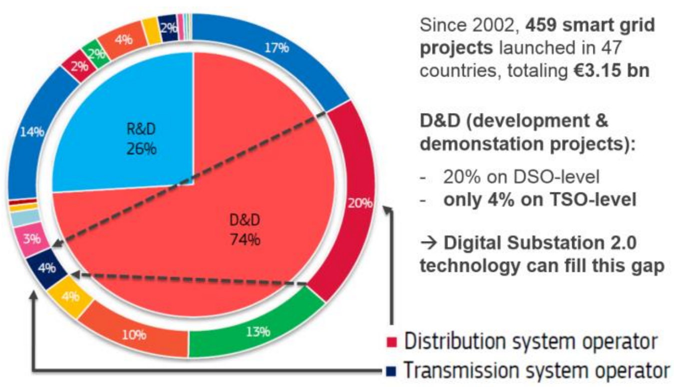

Fig. 2. Distribution of smart grid RD&D projects as per voltage levels [11]

Today, transmission-level voltages are usually considered to be 110 kV and above. Lower voltages, such as 66 kV and 33 kV are usually considered as distribution voltages, but are occasionally also used for long lines with light loads. As per the above referenced European Commission study [11], the majority of performed smart grids RD&D projects cover the distribution system voltage level and (still) not the transmission level of above 110 kV.

III. A Megatrend Drives the Enabling Technology

Digitization and automation are megatrends that gain momentum and profoundly transform our world. By 2020, an estimated 50 billion devices around the globe will be connected to the Internet. Apart from having a strong influence on our socio-economic environment, they also have a strong impact on the power generation and network technologies. The consequences with regard to the power infrastructure can be summarized as follows:

- Data collection and exchange are growing exponentially;
- Smart grids demand new capabilities and are triggering new business models and regulatory frameworks;
- Higher data volumes and better data quality prepare the way for automated grid control;
- Smart meters provide energy suppliers with the exact details of generation and consumption;
- Stress-dependent determination of residual life enable the transition from "break-and-fix" to "predict-and-prevent" operation and maintenance concepts; and
- Centralized asset management becomes possible.

The inherent smart grid functionality of the Digital Substation 2.0 technology complies with the above outlined characteristics and requirements.

IV. Technological Facets

A. Limitations by Conventional Substations

Existing medium and high voltage substations provide little flexibility for adopting new functionalities, increasingly required by external information systems [12-14]. It is difficult to implement retrospective additions of monitoring, protection and control. A further negative aspect is the limited interoperability due to vendor-specific designs. The mostly inadequate quality of measurements prohibits automated grid control functions and wide area monitoring. Regarding health and safety aspects, the cabling between the current transformers and the secondary equipment creates an inherent safety hazard in case of an open circuit situation.

B. Innovation by "Digital Substation 2.0"

The concept behind Digital Substation represents a disruptive[1], or even radical[2] innovation. As utilities are naturally cautious about such type of innovation, sequential familiarization is required. For a demonstration project, the use of either only one bay or a minor important substation is recommended. Digital and conventional technology (critical signals hardwired) might be operated in parallel for a time. Long-term trial operation will provide first-hand feedback on the system reliability and O&M[3] cost.

Digital data communication by station bus between the substation central control and the bay control and protection is standard since years. A key novelty by Digital Substation technology is that now also the primary equipment as well as the protection, control and monitoring devices are digitally connected via process bus. Binary communication based on fibre optic cables replaces traditional copper wiring using analog signals.

In the increasingly relevant IEC 61850[4] standardized data models and communication protocols as well as a uniform configuration language and a method to store such data, are described [15].

Further key aspects of Digital Substations are:

- IEDs[5] for protection and control of power equipment (transformers, circuit breakers, etc.);
- Novel measurement principles to satisfy emerging information needs (NCITs[6]);
- Functionality to support wide-area control infrastructure (quality & latency requirements); and
- Multi-vendor interoperability.

C. Competitive Advantages and Future Perspectives

Digital Substations are characterized by providing a higher operational flexibility and allow operation closer to the limits,

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1 Disruptive innovation represents a new product or service that enters the market and gradually displaces existing, established ones
2 Radical innovation represents a major technological breakthrough
3 Operation and maintenance
4 IEC 61850 is a unifying communication standard, one of the core standards relevant to smart grid
5 Intelligent electronic device
6 Non-conventional instrument transformer

even with transitional overloading. Cost-benefit analyses show significant OpEx[7] reduction by risk- or condition-based maintenance and fewer constraints by planned outages. The concept enables an improved asset utilization by stress-dependent determination of residual life. The potential for CapEx[8] reduction is highly project-specific.

Regarding future perspectives, Digital Substations enable:

- Further integration of renewables by automated control and monitoring of T&D[9] grids;
- Decision-making support for distribution control and outage management;
- Improved asset performance by utilizing big data;
- High quality analytics to extend equipment service life;
- Improved safety of personnel;
- Reduction of planned or unplanned outages;
- Optimized planning and allocation of capital and operational expenditure; and
- Streamlined engineering by interchangeability of specification data between stakeholders.

V. Market Situation

Substations of up to 400 kV using process bus concept and non-conventional instrument transformers are in operation. Out of the number of manufacturing firms offer corresponding equipment and services, in the course of the present study, 3 multinational corporations were interviewed with the goal to independently assess the market situation. The intention was to identify, what equipment is available on the market, what was successfully implemented and is in operation and what is presently still under research and development.

In the following, a non-comprehensive list of ongoing (demonstration) projects and existing pilot installations provided by the interviewed equipment suppliers is provided:

A. 1st Interviewed Multinational Corporation

- UK: 275 kV substation, overall process bus with non-conventional instrument transformers, merging units, protection IEDs, control IEDs and monitoring IEDs, 2017;
- Taiwan: 161/11 kV transformer and 161 kV line feeders, process bus realized for transformer differential protection, conventional instrument transformers with merging units, 2015; and
- UK: 400 kV GIS substation, process bus realized for distance protection, differential protection and control IED, non-conventional instrument transformers with merging units, 2015.

B. 2nd Interviewed Multinational Corporation

- France: RTE, Poste Intelligent 220/90 kV substations, 2015/2016;
- Switzerland: Linthal, Variable Speed Generator 255 MW (time-critical signals via optical process bus), 2015; and
- Denmark: Energinet, 420 kV Cable Station, 2014.

[7] Operational expenditures
[8] Capital expenditures
[9] Transmission and distribution system operators

C. 3rd Interviewed Multinational Corporation

- Finland: 123 kV GIS substation, process bus realized for distance protection, hybrid solution with hardwiring (conventional instrument transformers) and process bus (non-conventional instrument transformers with merging units) working in parallel, 2016;
- USA: 13 kV substation, process bus realized for overcurrent protection, conventional instrument transformers with merging units, 2016; and
- Peru: 220/138 kV substation, process bus realized for transformer differential protection, conventional instrument transformers with merging units, 2015.

VI. Sequential Familiarization by a Pilot or Demonstration Project

The actual market situation can be described as follows: Main suppliers have interconnected their equipment in different projects via IEC 61850. Difficulties still exist, as far as the standard allows variances in the implementation (mandatory/optional). Digitization on process level (e.g. real-time sampled measurement data) has started, but until now, only a few installations have been realized.

Among the strategic drivers for the need to familiarize with the new technology it was found that DSOs and TSOs[10] increasingly request data-intensive analytics from power producers with the final goal to establish smart grid solutions. Furthermore, it is expected that the manufacturing trend will be towards process bus with IEDs and NCITs. The digitization on the process level has started and global operational experience now has to be gained.

Considering a first-time utility rollout, it is recommended to implement a pilot bay or reference substation to get familiar with the technology and to exploit cost saving potentials. Extensive factory and site testing is recommended. The procedure of factory and site testing will change in so far as the practice of secondary injection (ampere/volt) is no longer applicable. Parallel to the process bus, copper wiring is recommended for critical signals. This level of conventional backup is recommended for the transition phase.

VII. Cyber Security

The increasingly high standardization of hard- and software makes modern information and communications technology (ICT) make automation and control systems vulnerable to cyber-attacks [16]. Consequently, critical infrastructure such as substations needs to be secured against such risks. Because the operating period of substation control systems is longer than the innovation cycle of IT products and applications, cyber security has to be designed to protect and secure equipment outside the life-cycle of the basic software products and operating systems.

From the system security point of view (IEC 62443), the corresponding hardware is available and needs to be configured following cyber security aspects. Communication security (IEC 62351) has to be taken into consideration due to the necessary data exchange with outside installations (e.g. load dispatch center, other substations or power plants). A corresponding Information Security Management System (ISMS) according to ISO/IEC 27000 needs to be implemented during the basic design and detail engineering phase in coordination with suppliers and the utility.

VIII. Conclusion

Digital Substation 2.0 technology represents a step-change innovation and is close to achieve the market breakthrough. It represents a smart grid enabling technology necessary for a power infrastructure based on bulk renewable energy infeed.

The concept supports the efficient integration of variable generation by centralized monitoring of T&D networks and finally automated grid control. Already today, the systems can provide decision-making support for critical network operation and outage management. The technology provides significant competitive advantages to plant and grid utilities, such as higher operational flexibility closer to limits with transitional overloading (dynamic loading) and improved asset utilization.

It ensures improved asset performance management by leveraging big data ("data mining" or "cloud-based analytics"). Optimised planning and allocation of capital leads to decreasing OpEx. The main productivity levers are the stretching (or shortening) of maintenance intervals, the prioritization of activities with regard to the importance of the asset and the risk of failure. Critical asset conditions can be recognized early and appropriate actions, e.g. ordering of spare parts with long delivery times, can be initiated in time to avoid unnecessary downtimes. The prioritization of service efforts based on the equipment conditions and its strategic relevance helps to optimize operational expenditure. Cost-benefit analyses show significant advantages by applying risk- or condition-based maintenance.

When taking a strategic perspective on the development of the future electricity supply, the Chinese initiative under the Global Energy Interconnection Development and Cooperation Organization (GEIDCO, formed by State Grid) needs to be taken into consideration [17]. A major element of their 2030 to 2050 strategic goal of intra- and transcontinental backbone networks builds on advanced direct current transmission systems and smart grid technology. They emphasize that "global energy interconnections are a combination of UHV[11] grids plus ubiquitous smart grids, forming a low-carbon platform for the supply of electricity with extensive coverage, high capability and a highest level of security and reliability".

IX. Acknowledgment

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[10] Distribution system operator / Transmission system operator

[11] Ultra-high voltage (up to 1,000 kV and above)

X. References

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XI. Biography

Ralf Bucher is employed at Lahmeyer International (a company of Tractebel/ENGIE) as power expert and project manager. He has more than 20 years of professional experience in large hydro and high voltage transmission systems, covering all phases, from initial studies to supervision of erection commissioning. From 1997 to 2001 Mr Bucher was employed as electronics engineer with Voith Siemens Hydro. He graduated in electrical power engineering and holds an MSc in environmental engineering. Mr Bucher is a certified reviewer for the Elsevier journals: Renewable Energy, Ocean & Coastal Management and Marine Energy. He is permanent member of the DIN committee on hydraulic turbines of the German engineering federation VDMA (mirror committee to IEC-TC4) and of the international steering team of the HYDRO conference series. Mr Bucher leads company-internal innovation projects, such as grid-scale battery energy storage systems and digital substation technology. In the course of his career, he has published 6 peer-review scientific articles and held more than 20 presentations at international conferences (e.g. World Hydropower Congress, HydroVision, World Future Energy Summit, International Conference on Ocean Energy, European & Asian Wave and Tidal Energy Conference and Power-Gen Europe & Africa).