Power Systems

Albana Ilo
Daniel-Leon Schultis

A Holistic Solution for Smart Grids based on LINK– Paradigm

Architecture, Energy Systems Integration, Volt/var Chain Process

Springer

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ISSN 1612-1287 ISSN 1860-4676 (electronic)
Power Systems
ISBN 978-3-030-81529-5 ISBN 978-3-030-81530-1 (eBook)
https://doi.org/10.1007/978-3-030-81530-1

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The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The work on the holistic architecture of smart grids has its roots in the research project FENIX.[1] Its goal was to control the reactive power exchange between the transmission and distribution grid using distributed generators' capabilities connected in a medium-voltage grid. The Volt/Var control in the medium-voltage grid was realised in an open loop. ZUQDE[2] project was crucial for the emergence of the holistic technical model of smart grids. The Volt/Var control was implemented in a closed loop, indicating that the secondary control, based on state estimator results, is technically feasible in a medium-voltage grid from an industrial point of view. At that time, I was with Siemens AG, Austria. I had the opportunity to thoroughly understand the different applications of energy and distribution management systems and participate in their design and implementation.

My research aimed to find a rational model to understand and design the future's power supply systems. The change at TU Wien was decisive to deal with this subject academically. During the research project of SmaGPa,[3] the smart grid paradigm *LINK* and the associated holistic architecture were developed.

The journey to introduce the holistic view and develop the *LINK*–Paradigm was challenging. It was often very depressing to pursue a different perspective than the usual one. I thank Prof. Wolfgang Gawlik, Head of the power system department, and Prof. Manfred Schrödl, Head of the Institute for Energy Systems and Electric Drives, for creating the primary conditions of my work.

I thank Daniel-Leon Schultis, my ex-student and my closest collaborator, for his engagement and excellent work: it was our joint decision to write this book.

I am grateful to many colleagues in various utilities worldwide who, through their discussions, have enabled me to know the different processes required to operate the power systems. I would also like to thank all of my colleagues at Siemens for their cooperation in carding various applications down to the smallest detail that has helped me get a solid understanding of transmission and distribution management systems.

[1] FENIX project funded under FP6 by the European Commission.

[2] ZUQDE project funded by "Neue Energien 2020" of "Klima- und Energiefonds", Austria.

[3] SmaGPa project funded by TU Wien, Austria.

Finally, I am incredibly grateful to my mother, Iliana. As former Vice Director of the Publishing House of the University of Tirana, she has repeatedly encouraged me to write and finish this book. I cannot go here without mentioning my youngest son Thomas. Although still a very young man, he was a worthy debater of various analytical methods in physics and mathematics.

Vienna, Austria Albana Ilo
June 2021

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About the Authors

Albana Ilo studied electrical engineering at the University of Tirana, Albania. In 1991, she moved to Austria and later received her doctorate from TU Wien with the topic "Flux distribution and power loss in transformer cores as a function of joint design" in 1998. She switched then to industry (Siemens AG Austria), where she was working on many projects worldwide as Recognised Expert, and later as Principal Key Expert Consultant in power systems. In 2013, she moved back to TU Wien. In 2020, she obtained the "Venia Docendi", thus qualifying her to teach in the area of "Electrical Energy Systems" with a habilitation on "*LINK*-based holistic architecture for future power systems".

She works on integrating distributed generation or smart grids and their impact on transmission and distribution networks. Her merit is the *LINK*–Paradigm and the holistic solution for smart grids derived from it that enables the decarbonisation of the economy (Sector Coupling) and the democratisation of the electricity industry (Energy Communities).

Daniel-Leon Schultis received the B.Sc. degree in electrical engineering at the Graz University of Technology in 2016 and the Dipl.-Ing. (equivalent to M.Sc.) from TU Wien in 2017. Since 2017, he has been working as Project Assistant at the Institute of Energy Systems and Electrical Drives, TU Wien. In September 2021, he received his doctorate in Electrical Engineering at TU Wien with the theme "Vertical Volt/Var chain control as part of the *LINK*-based holistic architecture". His works are honoured with several awards, including "Austria's Energy Award 2019".

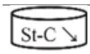
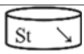
Abbreviations

AC	Alternating Current
AGC	Automatic Generation Control
APA	Active Power Appliance
BGA	Balancing Group Area
BLiN	Boundary Link Node
BPN	Boundary Producer Node
BRP	Balance Responsible Party
BSN	Boundary Storage Node
BVL	Boundary Voltage Limit
CAM	Control Area Manager
CC	Coupling Component
CD	Compensating Device
CHP	Combined Heat and Power
CoCe	Control Centre
CP	Customer Plant
CPG	Customer Plant Grid
CSA	Clearing and Settlement Agent
CVPP	Commercial Virtual Power Plant
CVR	Conservation Voltage Reduction
DC	Direct Current
DEG	Dynamic Equivalent Generator
DER	Distributed Energy Resources
Dev	Device
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DiC	Direct Control
DMS	Distribution Management System
DR	Demand Response
DSO	Distribution System Operator
DSSE	Distribution System State Estimator
DTR	Distribution Transformer
EC	Energy Community

EI	Equivalent Impedance
ElA	Electrical Appliance
EMS	Energy Management System
EPO	Electricity Producer-Link Operator
ESI	Energy Systems Integration
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission Systems
FCWG	Full-Converter Wind Generator
FENIX	Flexible Electricity Network to Integrate the eXpected "Energy Evolution"
GDPR	General Data Protection Regulation
GriLiO	Grid-Link Operator
HESS	Hydrogen Energy Storage System
HMU	House Management Unit
HV	High Voltage
HVDC	High-Voltage Direct Current
HVG	High-Voltage Grid
HVSO	High-Voltage System Grid-Link Operator
ICT	Information and Communication Technology
IoT	Internet of Things
ISO	Independent System Operator
LC	Local Control
LCC	Line-Commutated Converters
LFC	Load Frequency Control
LRM	Local Retail Market
LV	Low Voltage
LVG	Low-Voltage Grid
LVR	Line Voltage Regulator
LVSO	Low-Voltage System Grid-Link Operator
MC	Manual Control
MSC	Mechanically Switched Capacitor
MSR	Mechanically Switched Reactor
MV	Medium Voltage
MVG	Medium-Voltage Grid
MVSO	Medium-Voltage System Grid-Link Operator
OLTC	On-Load Tap Changer
P2Ch	Power-to-Chemicals
P2G	Power-to-Gas
P2H&C	Power-to-Heat and Cold
P2HESS	Power-to-Hydrogen Energy Storage System
P2T	Power-to-Thermal
P2X	Power-to-X
PC	Primary Control
PhST	Phase-Shifting Transformer
PV	Photovoltaic

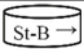
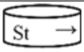
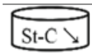
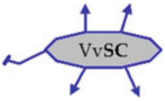
RES	Renewable Energy Resources
RPD	Reactive Power Device
RTU	Remote Terminal Unit
SC	Secondary Control
SCADA	Supervisory Control and Data Acquisition
SE	State Estimator
SGU	Significant Grid User
SM	Synchronous Machine
SmaGPa	Finding the Smart Grid Paradigm and New Architecture to enhance the Controllability associated with Future Power System Operation
SMPS	Switch-Mode Power Supply
SO	System Operator
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
StO	Storage-Link Operator
STR	Supplying Transformer
SVC	Static Var Compensator
SyC	Synchronous Condenser
TCSC	Thyristor-Controlled Series Capacitor
TCSR	Thyristor-Controlled Series Reactor
TSO	Transmission System Operator
TSSC	Thyristor-Switched Series Capacitor
TSSR	Thyristor-Switched Series Reactor
TVPP	Technical Virtual Power Plant
UML	Unified Modelling Language
VI	Violation Index
VMD	Voltage Maintaining Devices
VPP	Virtual Power Plant
VSC	Voltage-Source Converter
VvSC	Volt/Var Secondary Control
WoC	Web of Cells
WSC	Watt Secondary Control
WT	Wind Turbine

Graphical Symbols Used in *LINK*-Solution

Graphical Symbol	Name	Description
	Consuming device	Converts electricity into service for the end-user
	Devstorage	Consuming device with energy storage potential
→	One directional arrow of active power	The directional arrow of active power is coloured red
→	One directional arrow of reactive power	The directional arrow of reactive power is coloured blue
↔	Bidirectional arrow of active power	
↔	Bidirectional arrow of reactive power	
	*LINK*	It represents the *LINK*–Paradigm and the architectural elements such as grid, producer and storage links
	Link grid	It represents a grid area. The power flows are bidirectional: in or out of the grid area
↔ ↔	Loadinj	It presents the dual behaviour of a grid part like a **load** or **inj**ection → Loadinj
	Storage	Storage in general
 or 	Storage category A	The stored energy is injected at the charging point of the grid, such as pumped hydroelectric storage and stationary batteries

(continued)

(continued)

Graphical Symbol	Name	Description
 or 	Storage category B	The stored energy is not injected back at the charging point on the grid, such as the power to gas and batteries of e_cars
 or 	Storage category C	The stored energy reduces the electricity consumption at the charging point in the near future, such as cooling and heating systems (consuming devices with energy storage potential)
	Hz/Watt secondary control	It maintains a balance between generation and consumption (demand) within the control area and the synchronous area's system frequency
	Volt/Var secondary control	It maintains the voltage in the whole control area within the limits and the exchanged reactive power at the boundaries according to the schedules

Chapter 1
Introduction*

> Each time we get into this logjam of too much trouble, too many problems, it is because the methods that we are using are just like the ones we have used before.
> —Richard Feynman

In the last 20 years, many papers and books developed to investigate and design Smart Grids have been written. Smart Grid concepts are introduced, and various models are developed that lead to highly ramified and complex schemas. Different studies have focused on specific parts of power systems regardless of Smart Grids' integrity, leaving all efforts at the level of prototypes or isolated model regions. Results diverge instead of converging towards a complete Smart Grid solution.

So, what is the problem? "An extremely diverse and complex topic" is the answer. "… Each time we get into this logjam of too much trouble, too many problems, it is because the methods that we are using are just like the ones we have used before …" teaches us Richard Feynman [24].

The problem may have its origin in the definitions of the circulating Smart Grid concepts. Without elaborate concepts or paradigms characterised by unique and independent elements, serious design flaws and unclear operating procedures may result [43]. In this chapter, the scope of smart grids is specified, followed by an analysis of the state of the art of the most popular smart grid concepts such as Virtual Power Plants, Microgrids, etc. A descriptive presentation of power systems and the philosophical principles underlying the book are also given.

*Author: Albana Ilo

The original version of this chapter was revised: Figure 1.7 has been corrected. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-81530-1_5

A. Ilo and D.-L. Schultis, *A Holistic Solution for Smart Grids based on LINK–Paradigm*, Power Systems,
https://doi.org/10.1007/978-3-030-81530-1_1

1.1 Smart Grid Scope

Historically, power systems comprised the grid and the power plants: their extension ended at the points of connection with the consumers. The latter were treated as loads with individual behaviour. Figure 1.1a shows the scope of traditional power systems. It includes the grids of all voltage levels, i.e. High (HV), Medium (MV), and Low Voltage (LV) and the power plants mainly connected to the HV grid. Electricity storages such as pumped hydroelectric plants were classified as power plants. The number of power plants connected to the MV grid was minimal.

After the blackout that plagued the United States and Canada, on August 14th, 2003, the term "Smart Grid" was introduced. It was mostly related to the increase of the transmission capacity and level of automation in the grid [13]. The electricity crisis in California (2000–2001) gave the rise of Distributed Generation (DG) a significant boost [53]. The small Photovoltaic (PV) plants on house roofs transformed consumers during the day into electricity producers. A new category of customers appeared: the prosumers.

Over time, the meaning of Smart Grids term has evolved and now stands for modernising power systems and meeting all the requirements. There are several Smart Grid definitions ([51] European Commission; Smart Grid Mandate 2011; [3, 10]). According to [51], Smart Grids' area covers the entire power system right down to the individual electrical appliances in Customer Plants (CP). Figure 1.1b shows the scope of Smart Grids. It includes central and distributed generations connected across the entire power grid (in HV, MV, and LV levels) and customer plants. Smart Grids extend to the electrical devices in the customer plants.

1.2 State of the Art

The power industry has been challenged more than ever in the past 20 years. Its liberalisation [4] and the establishment of the electricity market [14] gave the power industry the first blow, followed by other difficulties caused by introducing new Renewable Energy Resources (RES) and DGs. At present, many countries are moving towards a renewable energy portfolio [15, 17, 23, 25], which increases the fluctuations in power systems. The electricity supply structure is also changing drastically due to many DG units [1, 6, 22, 53] interfering with the system operation at all voltage levels. This kind of development of the power industry is causing severe problems in the management and use of the existing transmission [33, 41, 44, 61] and distribution [27, 35, 55] grids.

To solve those problems, various Smart Grids concepts such as:

- Virtual Power Plants, VPP,
- Microgrids,
- Cellular Approach, and
- Web of Cells (WoC)

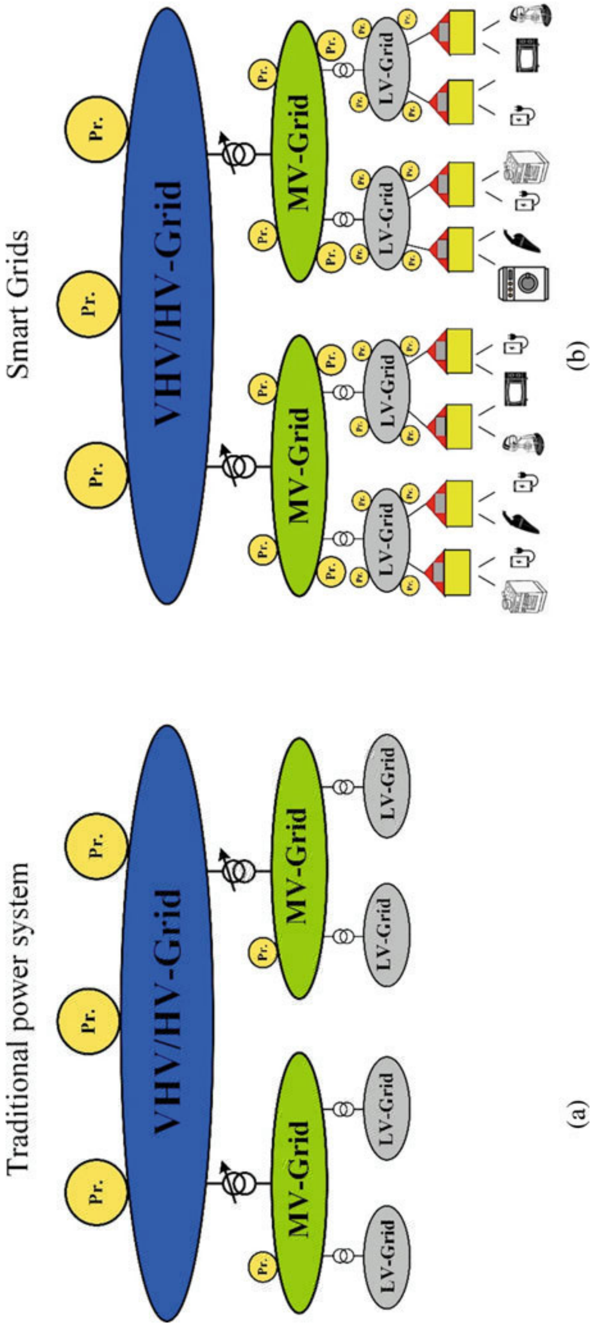


Fig. 1.1 Schematic representation of the scope of: **a** Traditional power system; **b** Smart Grids

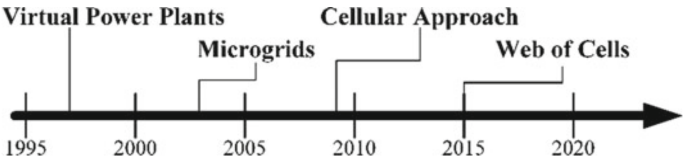


Fig. 1.2 The appearing timeline of the most popular Smart Grid concepts

have been developed for years. Figure 1.2 shows the timeline when these concepts first appeared in the literature. The book entitled Virtual Utility [2] introduced the terminology VPP to make DGs visible in the wholesale market. It quickly became clear that the concept of VPP could not address the technical challenges in terms of frequency and voltage caused by increasing the DG share: Microgrids concept was emerged to overcome these challenges [39]. Many scientists in different countries have started to use these concepts since their first introduction, providing various solutions to their cases. Most of them succeeded in changing these concepts' fundamental definitions to meet the specific requirements set in their projects. The detailed definitions of Virtual Power Plants [52] and Microgrids [32] concepts are still being discussed in various technical-scientific forums worldwide.

The Cellular Approach concept was introduced in 2009 in the research area Smart Grid [7, 12, 37]. A simple comparison shows that similar to Microgrids [62], the Cellular Approach [7] uses the same Matryoshka-doll principle in cells' settings. As emphasised in [38], both concepts are intertwined, and since then, the mixed name of "Smart Micro Grid Cell" was introduced.

In 2015, the landscape of Smart Grid concepts was enriched with the new WoC concept. The cell definition, which has evolved very dynamically in a short time [56, 18, 48, 56], is generic and does not appear unique in the literature [9, 28]. In the cell-based decentralised control framework WoC, cells are defined as "non-overlapping topological subsets of a power system associated with a scale-independent operational responsibility" [28]. Prosumers are not considered explicitly.

To solve the challenge of DG integration, the introduction and use of Smart Grid concepts have caused many other problems [45, 54, 60, 62]. The proposed solutions mainly were of a partial character, in many cases very complicated and with extremely ramified control schemes, making their practical implementation on a large scale almost impossible. Therefore, none of the solutions has practically crossed the boundaries of a research project. Unacceptable these problems, accumulated over time, sooner or later endanger the reliable and safe power systems' operation.

Additionally, the need for a new architecture is noted in the scientific community very early. The Smart Grid Architecture Model (SGAM) introduced in 2012 comprises a framework for the unique description of system architectures for Smart Grids (CEN-CENELEC-ETSI Smart Grid Coordination Group 2012). Its use is very complex and not broad enough for the new emerging requirement of decarbonisation of the economy [21].

Amidst such a research landscape with so many different concepts and restricted architectural model, it appears intriguing to pursue the question of whether the already existing concepts or their combination are likely to support a complete solution for Smart Grids. It is to be expected that any future extension of them or the development of the new concepts should enable the development of a complete Smart Grid solution.

1.2.1 Evaluation of the Most Popular Smart Grids' Concepts

Based on [51] Smart Grid definition, the complete Smart Grid solution is an answer seeking to solve the Smart Grid problems as a whole.

A complete Smart Grid solution should guarantee a stable, reliable, and cost-effective operation of a more environmental-friendly smart power system. It should also have the ability to ride through the transition phase and further without causing any problems.

1.2.1.1 Evaluation Methodology

The evaluation system consists of two parts: the assessment criteria and evaluation cloud chart.

Assessment criteria.

A complete Smart Grid solution is measured by assessment criteria that consist of a set of benchmarks or yardsticks against which the accomplishment, conformance, performance, and suitability. They are established by considering the following properties: each of them should be unambiguous, comprehensive, direct, operational, and understandable [34].

Ten unique criteria are defined to evaluate the Smart Grids' concepts (see A.1.1):

1. All voltage levels of power grids.
2. All electricity producers, regardless of size and technology.
3. All electricity storages, regardless of size and technology.
4. Consumers and prosumers.
5. All power system operation processes.
6. Data privacy protection.
7. Avoidance of big data transfer.
8. Market aspect.
9. Standardised structure.
10 Transition process.

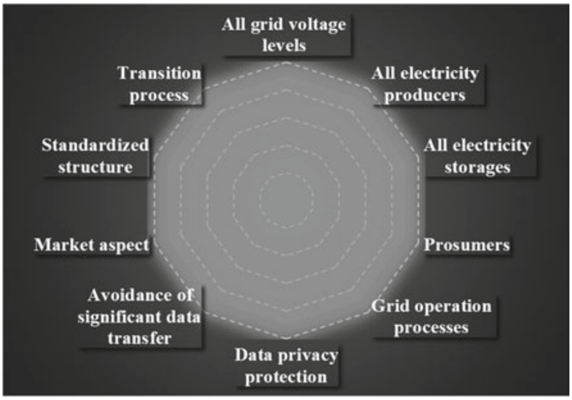


Fig. 1.3 The evaluation cloud-chart of an ideal Smart Grid solution. All criteria are fulfilled as a whole

Evaluation cloud chart

Evaluation cloud charts are used to present the assessment results to facilitate their interpretation and compare different cases. Figure 1.3 shows the evaluation cloud-chart of an ideal, complete Smart Grid solution when all criteria are fulfilled as a whole. The study performs only a qualitative analysis and draws results, which should be treated as a trend rather than a sharp rating.

1.2.1.2 Assessment of Smart Grids' Concepts

The detailed assessment for each Smart Grid concept is given in appendix A.1.2 Assessment of popular Smart Grid concepts. Figure 1.4 shows the evaluation cloud charts of each Smart Grid concept.

It shows that none of the solutions fulfill all the evaluation criteria as a whole. They all show almost the same shape, with a significant difference that the grid consideration is successively increased from the VPP solution, Microgrid, Cellular Approach and then up to the Web of Cells. The evaluation cloud-charts are not complementary to each other, which means combining solutions based on various existing Smart Grid concepts, VPP, Microgrids, Cellular Approach, and Web of Cells, cannot provide a complete Smart Grid solution.

1.2.2 Why Cannot Work the Actual Concepts

By examining the most popular Smart Grid concepts, it was found that they cannot characterise the manifold and the complexity of Smart Grids in their entirety. Their definitions are still under development and have not reached the final form. The derived architectural models are pretty complex and challenging to achieve, unlikely to be saved by downstream technical measures.

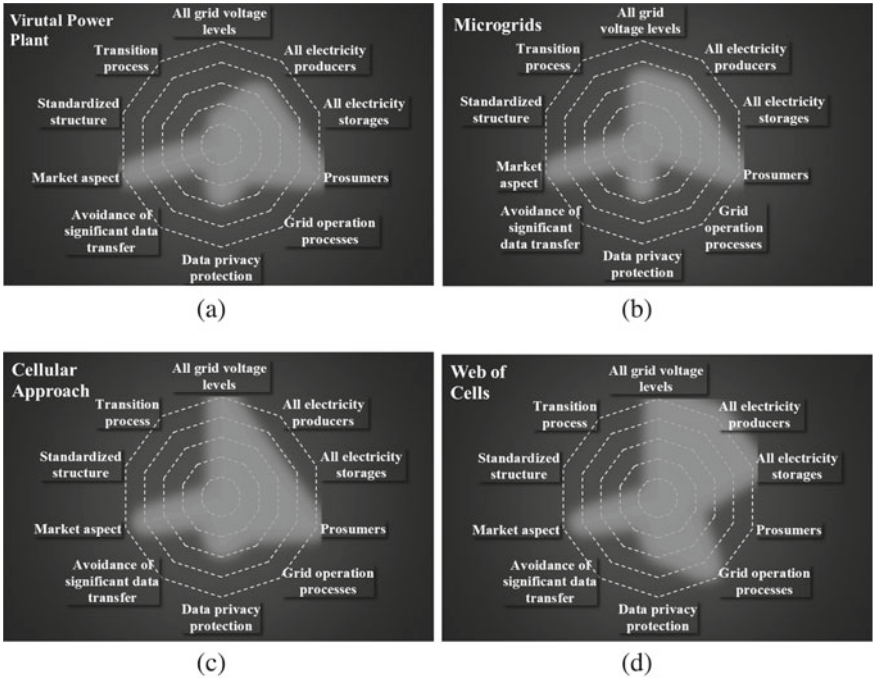


Fig. 1.4 The evaluation cloud-chart of each Smart Grid concept: **a** Virtual Power Plants; **b** Microgrids; **c** Cellular approach; **d** Web of Cells

The cause of the problem lies in origin, in the definitions of the popular Smart Grid concepts. The new architecting theory emphasises that concepts or paradigms with unique and independent elements are needed to avoid serious design flaws and unclear operating procedures [43]. For example, all Smart Grid concepts that include loads in their definition do not meet the basic principles of architecture theory to have unique elements because the term "load" can have several meanings in power system engineering. According to [30, 31, 47], the load may represent:

- A device connected to a power system that consumes power;
- The total power (active and reactive) consumed by all devices connected to a power system;
- A system portion that is not explicitly represented in a system model but is treated as if it were a single power-consuming device connected to a bus in the system model; and
- The power output of a generator or generating plant.

In addition to the term "load," the Microgrid definition also uses the ambiguous term "host power system;" Experts may interpret it differently.

The popular Smart Grid concepts do not fulfil the principle of the modern architecting theory. Their definitions are not complete and imply elements that are not unique and independent.

1.2.3 *Interdependent and Ambiguous Dimensions of SGAM*

The SGAM framework and its methodology are intended to present Smart Grid use cases from an architectural viewpoint, allowing it both- specific and neutral regarding solution and technology (CEN-CENELEC-ETSI Smart Grid Coordination Group [16]). It should enable the validation of Smart Grid use cases.

The SGAM framework consists of five layers representing business objectives and processes, functions, information exchange and models, communication protocols, and components. Each layer covers the Smart Grid Plane, spanned by electrical domains and information management zones (see A.1.3).

The modern architectural theory postulates independent and unique fundamental elements for a successful design [43]. Figure 1.5 shows an artistic representation of essential architectural elements through LEGO building blocks. The independent and unique elements depicted in Fig. 1.5a allow for a solid and unique architecture design. In contrast, the interdependent and ambiguous elements shown in Fig. 1.5b provokes crossing overs and often leads to significant problems up to ambivalent, highly complex architecture designs or no solution at all.

The Smart Grid Plane has a matrix structure (see A.1.3) with two interdependent and ambiguous dimensions (Domains and Zones). A similar interdependent and ambiguous nature is also present by the sub-dimensions. For example, on the one hand, DERs representing distributed generation and storage form a sub-dimension or domain. On the other hand, Customer Premises, which includes distributed generation (roof-PV facilities) and storage (battery of e-cars), are another sub-dimension or domain in the Domains dimension. Both sub-dimensions, DERs and Customer Premises, are closely intertwined, making these sub-dimensions dependent on each other. Similar interdependences and ambiguities may be found for each sub-dimension of the Domains and Zones dimensions. SGAM does not support the

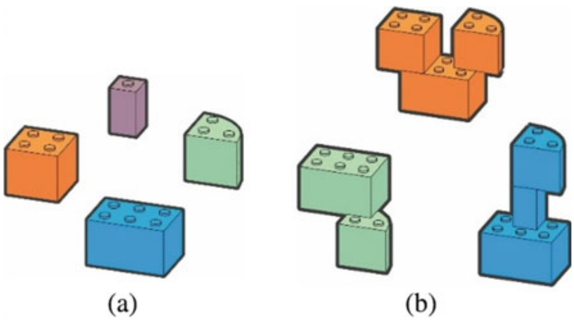


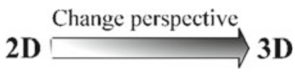
Fig. 1.5 Artistic representation of essential architectural elements through LEGO building blocks: **a** Independent and unique elements; **b** Interdependent and ambiguous elements (drawing S. Lengauer)

various storage options such as chemical storage, P2G, etc. (SGAM [16]) and should be extended beyond the original application to meet the time requirements [21].

1.3 Change of Perspective

Let's look at the schematically represented object in Fig. 1.6. It appears as a rectangle in the profile and horizontal plane and a circle in the vertical one. That is to say, in the two-dimensional perspective, different parties perceive the same object differently. The discussion on the "essence of the object" is therefore inevitable.

To get an objective picture of the whole situation, people first have to exchange their knowledge without prejudice, understand the other's arguments, and accept them—if there are no mistakes. In many cases, we may have to turn to an entirely new, unfamiliar point of view. In the picture, this is a change from the two- to the three-dimensional one. The discussed object is rather a square nor a circle. It is a cylinder.



This fact is an essential indication that a new perspective opens new horizons for a rational solution.

Let us extend the discussion to the area of Smart Grids, where for more than 15 years, controversial discussions have been flooding the scientific literature around

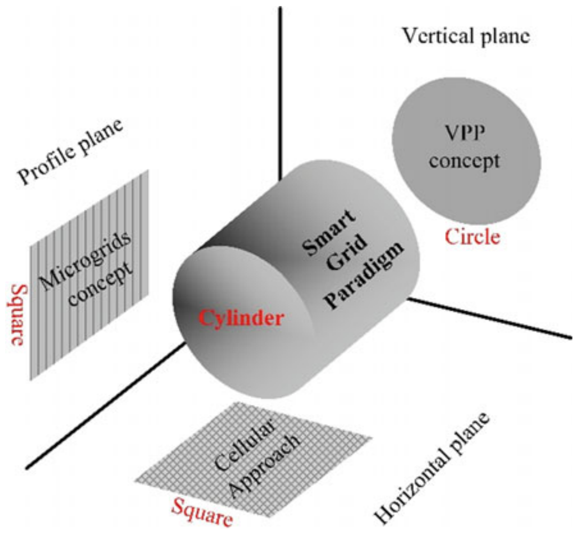
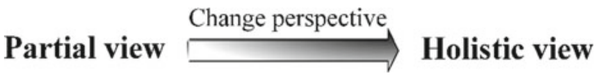


Fig. 1.6 Depending on the perspective, the Smart Grid concept is viewed and designed in entirely different ways

the world. Figure 1.6 also depicts the most popular Smart Grids concepts: Virtual Power Plants, Microgrids, and Cellular Approach. VPP concept is visualised by a circle put on the vertical plane because it was developed considering a partial aspect of Smart Grids: enabling the holder of distributed generators in the market. The microgrid concept is visualised by a square put on the profile plane because it was developed taking into account the partial technical aspect of distribution grids with Distributed Energy Resources (DER) leaving the transmission grid and the large power plants undefined. The Cellular Approach is also visualised by a square put on the horizontal plane. It attempts to further develop the Microgrids concept by considering the distribution and transmission grid through "connection and transmission corridors," respectively. As discussed in the case of the cylinder, the dispute over "the essence of the paradigm" is inevitable. If you want to assess the situation fully, you may need to change the perspective. This change is not always as easy as it seems. "Go to the other side and look from there" is only the first step. Again, we may need to turn to an entirely new, unknown perspective to define the Smart Grid paradigm. It requires a perspective change from the partial to the holistic view.



During this phase, a superordinate connection between some well-known operation processes as "Load/frequency control in high voltage grids" and "Volt/var control in medium voltage grids" was established: The holistic technical model was predicted as shown in Fig. 1.7. According to the prediction, the holistic technical model should include the entire power system, i.e., high-, medium- and low voltage levels, and the customer plants. In the SmaGPa project, scientists initially used the bottom-up or induction method to derive the Smart Grid paradigm *LINK* and the corresponding holistic architecture. The latter has shown the fractality feature of similar structural details. Misinterpretations or -decisions are pre-programmed in the bottom-up method. For this reason, the bottom-up approach was complemented by the top-down or the deduction method.

Scientists used the top-down method to verify the authenticity of:

- The architectural paradigm *LINK*, and
- The *LINK* Solution,

and to exclude any suspicion or misinterpretation. After a detailed analysis, the fractal pattern of Smart Grids was revealed. The *LINK*-Paradigm is derived from the fractal pattern. After that, the holistic technical and market model is conceived, followed by the *LINK*-based holistic architecture design. The latter enables the description and realisation of all processes required for the operation of Smart Grids, such as demand response, load/generation balance, and so on. The holistic architecture merges the electricity producers and storages (regardless of technology or size), the grid (regardless of voltage level), the customer plants, and the market into one structure without compromising data privacy and cybersecurity.

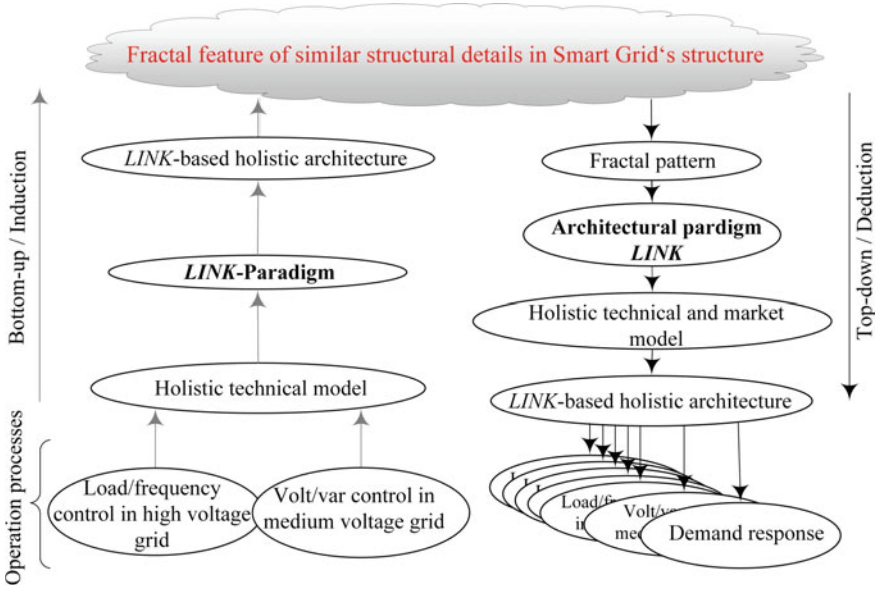


Fig. 1.7 Overview of the bottom-up and top-down methods used to find the *LINK*-Paradigm and design the corresponding holistic architecture

The predictions are confirmed, so we can assume that the holistic architecture is valid under the given circumstances and therefore useable for the practical implementation as shown in this book. The definition of the architectural paradigm of Smart Grids should be clear and contain unique elements so that experts or users cannot make different interpretations. Moreover, Smart Grids, including the entire power system, i.e., from the central and distributed electricity producers and storage through the transmission and distribution grid, and the electrical appliances in the customer plants, i.e., electrical devices, electricity producers (e.g., rooftop PV systems, and so on), and electricity storages, (e.g., the battery of e-cars, and so on) act as a single electromagnetic machine.

The consideration of the Smart Grids' integrity for the architectural design is necessary to achieve reliable and sustainable solutions. Otherwise, in a large-scale implementation, one-sided treatments such as today's battery assignment to a PV system can lead to ineffective solutions with severe environmental consequences such as the formation of mountains with non-recyclable batteries.

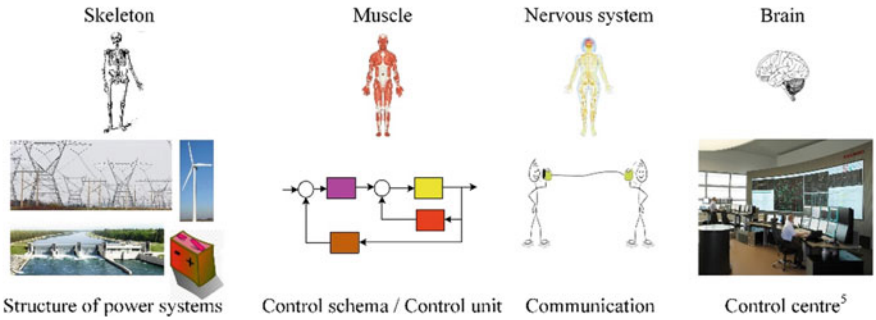


Fig. 1.8 The analogy between the human body and power systems (Control Centre Austrian Power Grid AG)

1.4 Vivid Perception of Power Systems

The world's most giant machines that humans ever built delivered around 25,721 TWh [29] electricity via the power grids in 2017. It is the power system, an interconnected structure of electricity production facilities, wires, transformers, and much more, that keeps the lights on for the homes, buildings, streets, offices, factories, etc. They are very complicated and impossible to model in laboratories; experiments with the physical systems are in almost every country prohibited by law. These features make power systems unique in the landscape of today's technologies; their holistic view is quite complicated.

Figure 1.8 shows a vivid perception of power systems that were crucial for designing the *LINK*-based holistic architecture. It is based on the analogy between the human body and power systems as follows:

- The interconnected structure of electricity production facilities, wires, transformers, and so on is viewed as the skeleton of the human body;
- The control units are considered as muscles, which for example, can close and open the water or gas injectors to increase or decrease electricity production and so on;
- Communication, which includes measurements, is viewed as the nerve system, which contains receptors, that carries information or instructions from the brain to the muscles; while,
- The control centre is considered the brain that controls and operates power systems reliably and safely.

1.5 Philosophical Principles Underlying This Book

Achieving a solution to many of the practical challenges of today's society requires a philosophical statement. In terms of genetic engineering, artificial intelligence, environment or climate: Everywhere, norms and considerations, pros and cons are essential, thus creating the ideal conditions for philosophical discussions and reflections. It is now clear that the new electricity era is a technical, social, and political issue.

The issue of Smart Grids raises many questions, such as the de-carbonisation of the power industry, the role of consumers, the data privacy, the decentralised or centralised solutions, the modernisation or digitalisation of the power grid, etc., which require a clear statement to promote the appropriate technical solution. The questions have been widely discussed in the scientific fore worldwide, but opinions and recommendations remain very different.

The following principles have served as a common thread for the design of the technical solution presented in this book:

- Overall, you would set a sign in total, although your contribution to saving CO_2 could be minimal: It is much better than doing nothing. This principle is reflected in the large-scale integration of distributed renewable energy resources that drive the power industry's de-carbonisation in Smart Grids;
- Reducing the ecological footprint is a necessity to enable the continuity of human life on earth. In terms of Smart Grids, this is reflected in the efficient use of the power industry's existing infrastructure:
- The privacy of the individual, customer, or company is inviolable. In terms of Smart Grids, this is reflected in the reduction of the technical solutions' information;
- The technical solution should guarantee freedom of choice for every customer and should not be discriminatory.

1.6 Outline of the Book

The second chapter gives an overview of the methodology used in this book. The fractal structure's identified signature of Smart Grids, the so-called Smart Grids' fractal pattern, constitutes the *LINK*-Paradigm's foundation. The derived holistic model and architecture are broadly presented. Additionally, it is given a compact description of the control chain strategy and some processes such as the market participation harmonised with the technical holistic architecture, demand response, etc. The third chapter is dedicated to the Energy Systems Integration by treating the Sector Coupling and Energy Communities in the *LINK*-Solution context; meanwhile, the coupling with the non-energy sectors will be treated in another edition of this book. Chapter four deals with the Volt/var process of the control chain over the high-, medium- and low voltage levels and customer plants. The traditionally, recently used and *LINK*-chained control strategies are analysed and developed.