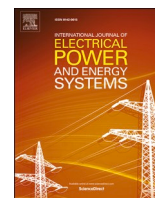


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Towards holonic power and energy systems – A novel ICT architecture as enabler for resilience

Christian Rehtanz^{a,*}, Andreas Ulbig^b, Rajkumar Palaniappan^a, Timm Faulwasser^a, Selma Saidi^a, Anke Schmeink^b, Christian Wietfeld^a^a TU Dortmund University, Department of Electrical Engineering and Information Technology, Otto-Hahn-Str. 6, 44227 Dortmund, Germany^b RWTH Aachen University, Faculty of Electrical Engineering and Information Technology, Schinkelstr. 2, 52062 Aachen, Germany

ARTICLE INFO

Keywords:

Energy system automation
 ICT architecture for energy systems
 Holonic automation architecture
 Digital twin
 Digitalisation of energy systems
 System-of-systems

ABSTRACT

In the ongoing transition towards distributed Renewable Energy Sources (RES) and the concurrent transformation of critical energy infrastructures, the efficient coordination of load, storage, and generation flexibilities while avoiding grid congestion is crucial. To orchestrate the growing myriad of distributed devices, digital solutions based on scalable information and communication technologies (ICT) that go far beyond the existing state-of-the-art, are the key enablers.

To open a new avenue towards robust and resilient power and energy systems, this paper proposes the concepts of holarchies and holonic structures as underlying design principles for grid automation and coordination of flexibilities in power and energy systems. We argue that the holonic concept and its theoretic underpinning enables designing and building future resilient power systems that can cope with the otherwise overwhelming complexities of the energy transition. Our long-term vision is that the proposed holonic concept encompasses already existing trends in power and energy systems, i.e. decentralization, digitalization as well as observability and controllability improvements, into one holistic framework, whereby holistic integration is likewise pun and serious ambition. Beyond the existing holonic approach in general and partly for limited power system applications so far, our design proposal encompasses ICT infrastructures and the data domain into a consistent novel architectural approach.

Holonic structures, or holarchies, extend and build upon the recursiveness and self-similarity of autonomous sub-structures, i.e. holons, of a system. It is a system-of-systems approach and, thus, conceptionally, very different from existing and well-known multi-agent system approaches. In essence, holonic concepts allow for the formalisation of hierarchical system relations regarding physics, information, and data using a part-whole architecture. Hence, they are well-suited for the conceptualisation of automation functionality across all dimensions of the cyber-physical domain of energy infrastructures and potentially also beyond.

This paper investigates holonic structures from different novel perspectives, such as control and automation, system modeling and digital twins, as well as the corresponding ICT-infrastructure and data requirements. Three case studies are drawn upon as examples to illustrate how holonic concepts and approaches are already emerging in power and energy systems operation.

© 2017 Elsevier Inc. All rights reserved.

1. Introduction

With the defossilization of energy systems as part of the on-going energy transformation, electrical energy generation is becoming decentralised due to the rising RES integration and, in turn, declining numbers of large generators and its rotating machinery, while at the

same time, load demand is growing due to electrification and sector coupling trends [12]. Functional differences between grid levels are more and more vanishing [3]. Such developments contribute to a significant rise in the complexity of electric power and energy systems worldwide, generally leading to growing usage and stress on energy infrastructure and worries about future reliability [3]. This further

* Corresponding author.

E-mail address: christian.rehtanz@tu-dortmund.de (C. Rehtanz).<https://doi.org/10.1016/j.ijepes.2024.110283>

Received 6 March 2024; Received in revised form 31 July 2024; Accepted 1 October 2024

Available online 8 October 2024

0142-0615/© 2024 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

increases operational risks and instabilities [4], for instance caused by low-inertia situations [5], necessitating greater operational flexibility for mitigation [68]. This transformation of the energy sector as a whole renders existing power and energy infrastructures – which currently rely on centralised monitoring, operation, and control concepts (top-down) – increasingly inadequate for guaranteeing supply security, providing grid control, and maintaining stability in an ever-more decentralised energy system [8]. Instead, decentralised approaches for grid monitoring, operation and control (bottom-up) are needed [9,11]. In turn, this entails new opportunities such as bottom-up system restoration using DERs [12].

Today, conventional power and energy system automation comprises hierarchical coordination structures and market mechanisms but not yet holonic concepts. Although certain holonic properties can already be found in multi-agent approaches used for distributed organisation or optimisation purposes in power and energy systems, this is only part of the way towards holonic system design. Recursiveness, which means that holons contain other holons as subsystems, differentiates a holarchy from the classic multi-agent systems. It also incorporates the hierarchical and layered perspective, which is a crucial aspect for many technical systems, e.g., consider voltage levels power systems.

In response to the escalating complexity and the need to maintain the resilience of the entire system, this paper proposes a novel holonic framework for automation, control, and operation in power and, more generally, energy systems. This approach towards the design of a system of systems is created to render energy systems resilient against disturbances and failures across varying grid levels and sectors and to ensure robust system operation.

A *Holon*, according to The Free Dictionary¹, is an autonomous, self-reliant unit. The interactions of these autonomous units across hierarchically structured levels and layers form the holonic system. Essentially, a holonic system employs a system-of-systems perspective, where each subsystem functions autonomously and as self-sufficiently as possible, it may contain further subsystems thus becoming an integral part of the complete power and energy system. This contrasts clearly with the current monolithic, top-down operations and automation of power and energy systems managed by centralised control centres. Surpassing centralised approaches, the paper proposes the development of decentralised holonic control structures that perform highly automated and even potentially autonomous functions for the holonic subsystems.

The usage of Holons and the holonic approach for power and energy systems has, to our knowledge, first been proposed in [33] in 2007 and has since been taken up steadily in the power systems community [34]–[61] (see Section 2.3.1 for an extensive discussion). However, there exists not yet an overall holonic architecture for power and energy systems considering the whole operational spectrum, i.e. from implementing power and energy system related functions and applications to the underlying ICT layer as well as data acquisition, communication and processing.

Success in the holonic system-of-systems approach necessitates the invention of new, scalable, and distributable methods for the operation and automation of power and energy systems, which must address architectural aspects of automation and control, communication, and information and data management. Hence, new methods and technologies for distributed communication infrastructures, data structures, and computer systems to be jointly designed in line with the holonic paradigm are required. To address these challenges is the intention of this paper.

Future control strategies for power and energy system operation and automation must be scalable across all system levels and resilient against various disturbances and uncertainties – these features are not provided

by classical SCADA systems. The associated data infrastructures should leverage the elsewhere widely established principles of data sovereignty and distributed data storage in line with the anticipated advancements in distributed cloud technologies. The emergent trends of decentralised edge and embedded computer infrastructures function as dispersed automation components, enabling process migration and allocation even amidst disruptions. Similarly, communication infrastructures must operate in a decentralised manner, bolstering resilience against system disturbances. The proposed holonic system-of-systems architecture should be realised through the interplay of cutting-edge research trends in these related disciplines and their application in the power system domain.

The paper is structured as follows. Section 2 presents an in-depth structural analysis of the new holonic approach, examining the requirements for power system operation and the methods and infrastructures required for computing, data, and communication, as well as reviewing the state-of-the-art in the relevant research fields. The objective is a highly automated overall system composed of autonomous, resilient sub-components, thereby achieving unprecedented levels of system resilience. Section 3 showcases examples from recent research and development work of some of the crucial building blocks for holonic power systems. The paper ends with brief conclusions of the benefits of holonic architectures and structures in power and energy systems in Section 4.

2. Holonic architectural paradigm for the design of power and energy systems

2.1. Fundamental architectural concept and vision

The transition towards distributed and defossilized electric power and energy systems necessitates entirely new system automation methods, grid operation, and associated market activities, including ancillary services. These methods reconcile system resilience and partial autonomy with the intrinsic volatility of renewable energy sources. To meet these objectives, we propose ‘holonic’ architecture concepts for power system automation, control and operation to be complemented by novel methods and technologies in the underlying enabling fields.

Beyond the basic definition of a single holon as an autonomous self-reliant unit, a holon is a distinct entity built from a collection of subordinates while being itself part of a larger entity. The basic idea of holons originated from Arthur Koestler, an author and philosopher, while describing the behavior of complex social systems in his book “The Ghost in the Machine” [13]. The interaction of parts of the systems, called holons, according to local autonomy and cooperation, as well as the incorporation of hierarchies within the distributed structure, are features of holonic systems. Therefore, we can refer to what Koestler called holarchy as a *system-of-systems*: each subsystem is a functional entity or (sub) *whole* in and of itself, having more or less similar structures and properties compared to the other sub-systems, but is also a *part* within a similar hierarchically structured aggregated system entity, i.e. a (super) *whole*. This *part-to-whole* relationship is the defining feature of holons. In order to facilitate the understanding, we begin by outlining the proposed holonic concept in the following informal definition.

3. Definition (Holarchy and holons)

A holarchy is a system-of-systems structure with vertical and horizontal interconnections.

- The holarchy and its elements, the holons, interact with their respective environment through the exchange of energy, information, and data; they are thus intrinsically open systems.
- A holarchy stretches across different dimensions of technology: physical components, provided functionalities (e.g. protection,

¹ <https://www.thefreedictionary.com/holon>.

automation and control), data spaces, and enabling ICT infrastructure.

- The elements of a holarchy, the holons, admit hierarchical super- and subset relations as well as neighbourhood relations.
- The holons allow for substantial heterogeneity on a physical and hardware level, while functional principles share a high degree of similarity between holons on the same hierarchical level.
- The underlying coupling structure is cyber-physical and dynamic in nature, whereby endogenous (intentional grid decoupling) and exogenous causes (contingencies and faults) can trigger topology changes.

A holarchy thus shares design requirements over all technology dimensions (hardware, communication, automation and control, as well as information and data):

- The trade-off between resilience against faults and attacks, installation and operation costs, and operational capabilities is actively addressed in the design of holonic system architectures.
- Holons allow for both intentional and unintentional decoupled/islanded grid operation for limited amounts of time (e.g. subject to energy availability). Temporary decoupling can be admitted over all constitutional dimensions: energy, communication, information and data
- Holons allow for plug-and-play interaction among each-other and adapt autonomously
 - o to changes of their inner structure,
 - o to the dynamics of their environment outside of the holarchy, and
 - o to metamorphic changes of the holarchy itself.
- The functionality a holon provides within the holarchy can be adjusted at run-time without hardware adaptation.

The established and mature grid operation and management rely on a hierarchical structure. That is, large generators provide power injections which are first transmitted and then distributed through several layered voltage levels to the consumers. However, the increasing structural changes, i.e. decreasing number of large-scale generators and with it lacking rotational inertia, increasing numbers of RES and DER on the distribution grid, increasing share of volatile renewables, induce architecture bottlenecks in the traditional top-down operation. Prime examples are growing redispatch costs and the need for improved TSO-DSO coordination,

At this point it is fair to ask, how holonic architectures differ from multi-agent concepts from fractal concepts. According to B. Mandelbrot [14], the defining feature of fractal structures is self-similarity, i.e., on different levels all subsystems are of identical structure. Hence fractal concepts fail to capture the heterogeneity of different substructures in power systems. Prime examples are different demand DER characteristics of residential and industrial prosumers. In contrast to fractal structures, multi-agent systems often refer to flatter hierarchies. In, e.g., hierarchical distributed control, one agent may have the role of a coordinator [10]. However, multi-agent structures fail to capture systems-of-systems architectures adequately and they often struggle to allow for varying degrees of self-autonomy.

A prominent example highlighting the shortcomings of fractal and multi-agent structures are rapidly growing costs for generator redispatch and curative actions [15]. In Germany, it is already under investigation how to refine the so-called *Redispatch 2.0* [16,17] DER generation management scheme, which is currently rolled out nationally in all distribution grids for controllable units of 100 kW and larger, down to even smaller DER units [18] for future implementation. This means that a heterogeneous set of systems (hence not a fractal structure) shall be coordinated. The coordination has to happen across several nested voltage layers, hence the multi-agent setting does not apply.

In contrast, from the holonic perspective all holons entailed in a distribution grid, which is another holon on another layer, can be tasked

with assessing the flexibility autonomously and to communicate, via a holonic ICT backbone, this flexibility to the upper-level holon in the transmission system. Likewise, neighbouring transmission holons can be tasked with coordinating with each other. Moreover, in case of contingencies on the transmission level, e.g. communication or line faults, holons in the distribution system can be tasked with defining system boundaries of temporary islanded, viable sub-grids, which can survive autonomously for a limited time period, and with operation such autonomous sub-grids and coordinating them with each other. In existing top-down operated state-of-the-art power systems, functionalities such as autonomous operation of islanded sub-grids, and linked to this black-start capabilities, are very complex, if possible at all, to implement. Put differently, in contrast to top-down operation of traditional power systems, holonic architectures provide a canvas to operate bottom-up and to bolster resilience through purposeful self-autonomy locally as much as possible. Crucially, the holonic structure extends to the underlying enabling ICT technologies, which is both a key enabler and prerequisite for virtually all decentralized, bottom-up grid operation schemes.

Conceptually, it can be leveraged to make large-scale infrastructures, e.g., power and energy systems, more resilient by design – both in the actual (near) real-time operation as well as in the various planning phases, i.e. with short, medium and long-term horizons. First elements of the application of holonic concepts for resilience in energy systems are emerging, i.e., they can be observed and identified in the literature, see Section 2.3.

The pivotal long-term research questions motivating this approach are the following:

- How can the rising challenges regarding complexity in today's power systems be tackled by a new holonic automation, control, and operation architecture?
- Can the holonic approach as an organisation and coordination method be used to make grid operations more resilient?
- How can the power systems' ICT layer, comprising communication, computation, and data infrastructure, be designed as a lever for reducing the impacts of disturbances, uncertainties, and risks in power and energy system operation?

The distinctive *part-to-whole* relationship of holons, characterised by partial operational autonomy can be discerned in alignment with the cellular concept [19] that dissects the multi-dimensional, interconnected multi-energy system into substructures. Essentially, the various components of the power and energy system exhibit structural similarity. For example, grid areas at different voltage levels – connected to generators, loads, and storage – both provide and necessitate controllable flexibility.

The proposed holonic structure amalgamates these subsystems, each exhibiting a degree of autonomous behavior, into a hierarchical power and energy system framework. This hierarchy is inherently determined by a combination of remote large-scale and central energy resources, e.g., hydro and offshore wind energy as well as pumped-hydro, and local, Distributed Energy Resources (DER), e.g., photovoltaic and wind energy as well as battery storage, interconnected through multiple power grid levels and other energy carrier grids. The overarching structure of electrical power systems is depicted in Fig. 1, illustrating an example of a grid area represented by a single holon as a fundamental structural element in the proposed architecture.

The representation of a grid area as a holon is sketched in the bottom half of Fig. 1. The grid users (prosumers – circles with red icons), such as industrial consumers, households with PV, storage, heat-pumps, or renewable feed-in, are managed by the holon. Likewise, they are instances of holons that manage their individual objectives considering e.g. market prices, weather conditions, or constraints from sector coupling. These grid users can provide a certain active and reactive power flexibility if either the market or the grid operation requests it.

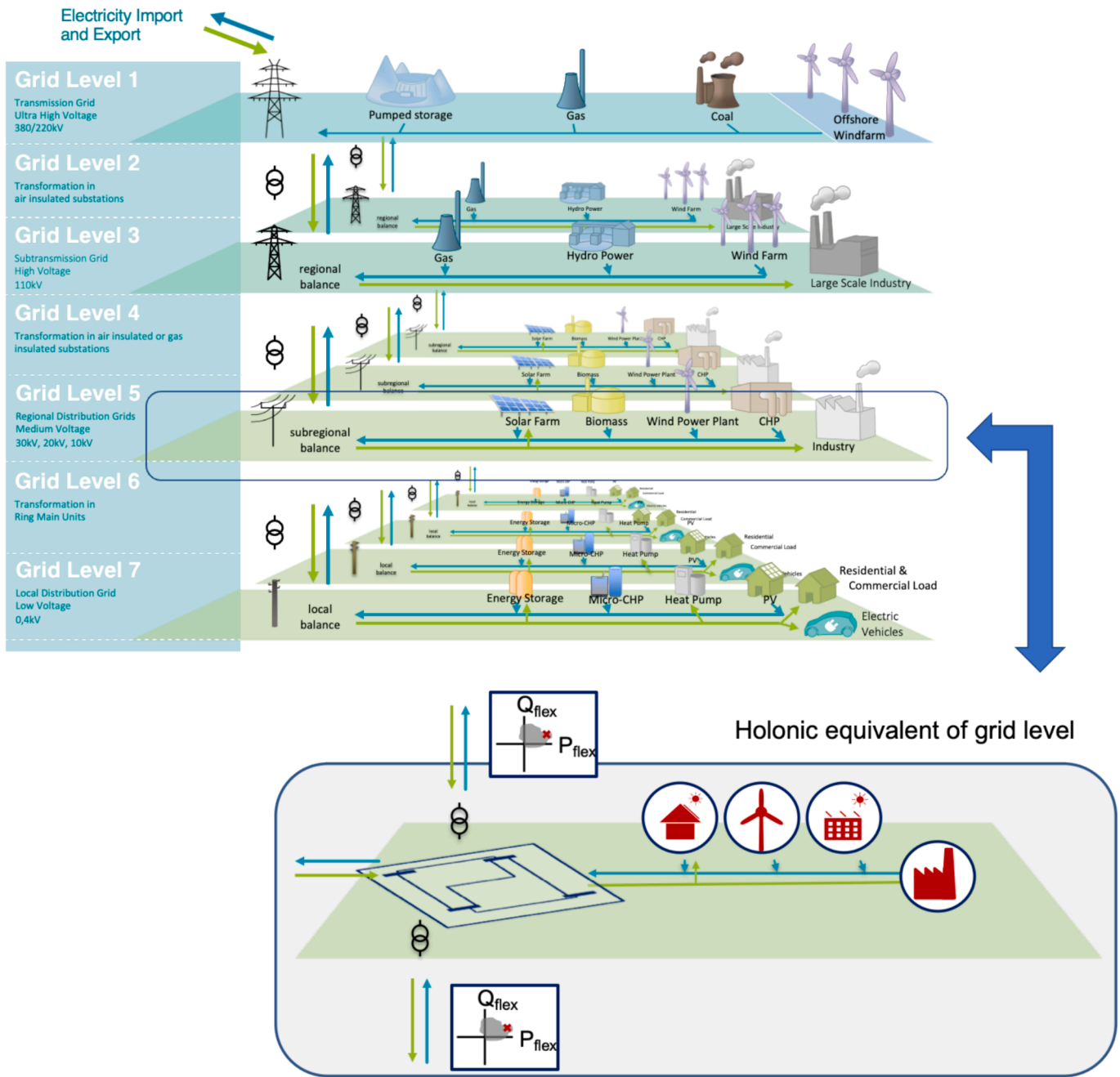


Fig. 1. Power system architecture and exemplarily marked holon as a structural element (i.e. subsystem).

Each holon must coordinate its current or expected future behavior concerning its internal grid constraints, i.e., line capacity limits.

In contrast to mere aggregations, the targeted holic system architecture is subject to hierarchical sub-relations, for instance, the established primacy of high-voltage sub-transmission over medium-voltage distribution. At the same time, holic systems allow and require partial self-sufficiency and autonomy of the subsystems. The term 'autonomy' is used in the following in the sense of, as far as possible, high automation of processes according to the definition of autonomous levels in power systems of the German Association for Electrical, Electronic & Information Technologies (VDE) [20].

The behavior and flexibility of the subordinated holons at the lower voltage grid levels must be considered as additional services or constraints. The holon itself shall provide the lumped information of its behavior, including all connected instances to the superior level. Requests from the superordinate level shall be executed in a coordinated

way to the connected instances after considering the grid constraints. The architecture leads to new algorithms and modeling required to operate the system and to coordinate the exchanged information between the holons and users along with all timelines for the energy market, grid, and ancillary services purposes, considering underlying uncertainties.

In contrast, the state-of-the-art in power and energy system supervision, control, and automation systems is still dominated by monolithic solutions specific to each grid level, as visualised on the left side of Fig. 2. On the transmission level, full supervision based on complete observability via measurements is assumed for each grid area. The system boundary is towards lower grid levels, which means that the detailed and growing complex behavior of these subordinated levels is neglected in almost all the real-world power grids, and towards neighboring grid areas, where information exchanges and partly even central coordination procedures are foreseen [21]. The established supervision

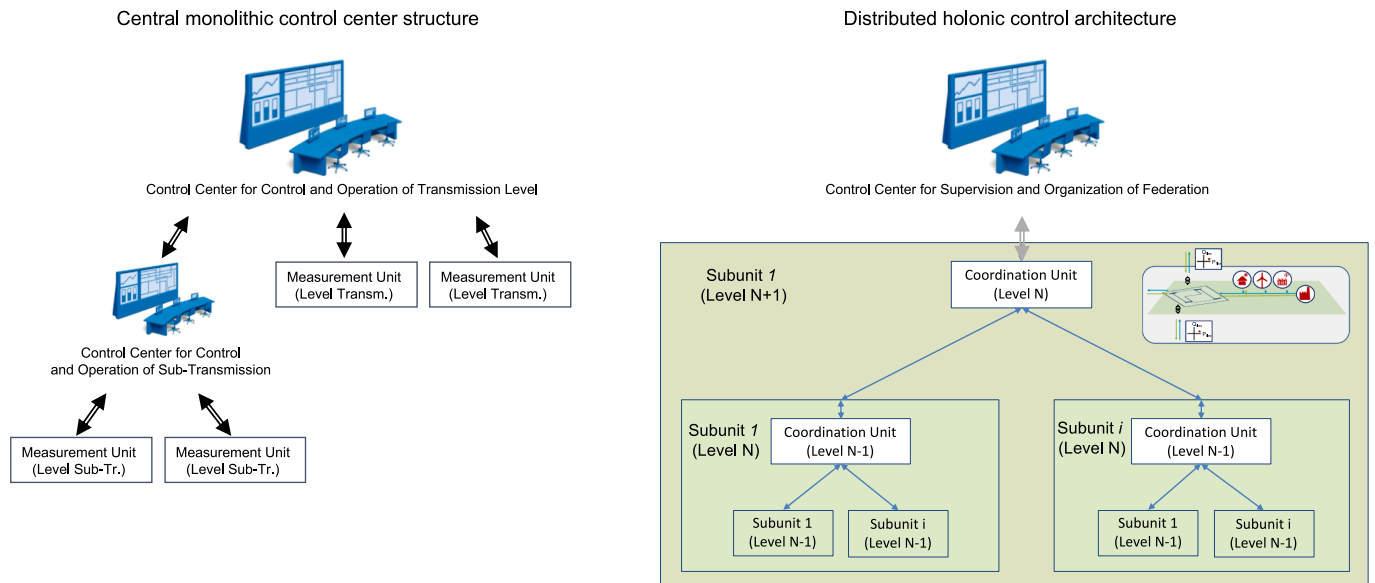


Fig. 2. Comparison of central monolithic (left) with distributed holonic control architecture (right).

on the medium and low voltage levels is, at best, marginal but mostly still non-existent in real-world power system operations [22,23,24]. However, the first approaches for distribution grid supervision are reaching increasingly higher Technical Readiness Levels (TRL) and pilot applications [25,26].

The right side of Fig. 2 represents the recursive organisational approach of holons. Each holon of a specific system level receives information from subordinate levels, coordinates it autonomously for its own level, and provides services to the superior level. The control centre level is for the overall supervision of the distributed control and supports the federation of data, information, and methods within the complex hierarchical system. The distributed holonic control architecture enables (more) autonomous sub-grids, e.g. with various autonomy levels depending on storage and control capabilities. Control tasks and responsibilities are shifted from a single control centre (central control), to several lower-level coordination units, e.g. on level N, N-1, etcetera (decentral control). Depending on the specific grid management tasks, these coordination units would correspond to DSOs and aggregators on the enterprise level. Whereas (more) active distribution grids need to be operated in general by DSOs, certain functions, e.g. flexibility provision, would become the direct responsibility of flexibility aggregators etcetera.

The vision or requirements for future holonic power and energy systems are driven by the following key (design) features:

- The holonic architecture is a system-of-systems design paradigm in which holons as subsystems achieve a fundamentally higher degree of resilient and autonomous operation with respect to disturbances or failures in power systems, communication, data, or computation infrastructure, where
- resilience means to assure or guarantee services despite disturbances or failures,
- resilience will be achieved by distribution and decentralisation supported by ICT task migration, redundancy, and adaptation or reconfiguration.
- Novel methods and algorithms inspired by the holonic design paradigm are created, validated, and evaluated for supervision, control, automation, and operation of power and energy systems, which are
- scalable in the sense of being applicable to all grid levels or parts of the grid equally, in the holonic architecture,
- conveniently structured systems of holons, where each holon comprises its own part of the power system, i.e., systems of (power)

systems design approach. This includes an informative aggregation of behavior and ancillary service capabilities between super- and subordinated subsystems based on data-driven modeling.

3.1. Architectural integration of power system automation, data, communication, and computation perspectives

The overall structure needs to be designed such that the system can be split into separate subsystems, i.e., holons, which operate autonomously based on local information and data models. The underlying communication infrastructure needs to mirror the holonic power grid infrastructure. The need for autonomy also holds true for the communication infrastructure itself, which requires running in separate holons in case of failures of superordinated communication networks. Local communication should be preferred, where central single-point-of-failure instances, such as the routing servers in contemporary mobile communication, must be avoided. The redundancy of various communication channels of different kinds and their distributed and robust management could be one direction to be considered.

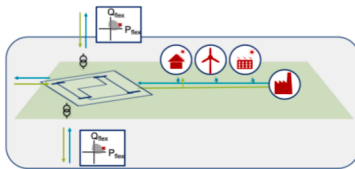
Fig. 3 specifies the different required technical levels and scientific disciplines to be included within the holonic architectural approach.

Another pivotal element in the design of such completely new supervision and control architectures is the consideration of embedded components providing real-time execution of distributed supervision and control applications as well as communication tasks. The flexible offloading of algorithms to the hardware infrastructure and shifting them in cases of computing and embedded device failures must be provided technically. The deployment of algorithms and software on embedded devices has to be addressed within the holonic architectural approach. The resulting system and the employed algorithms have to be robust against device and communication failures. Embedded systems combined with novel communication technologies and infrastructures are enablers for fundamentally distributed and scalable algorithms, including data handling, which in turn are critical for resilient and holonic power systems.

Future trends and fundamental interdisciplinary research in power system automation, data, communication, and computation are closely interwoven with the new holonic system architecture. Classical power system algorithms and standard models need to be reformulated to be easily scalable throughout the grid levels and to aggregate models from lower levels. Besides the mathematical reformulation, new data sources

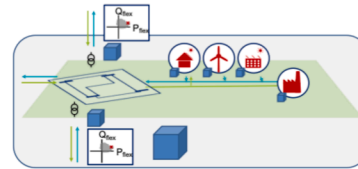
Algorithms from power systems perspective

- Scalable algorithms for control, automation and operation of grid level (holon) itself incl. ancillary services
- Simplified/merged model of behaviour, flexibility, and controllability for superordinate grid level



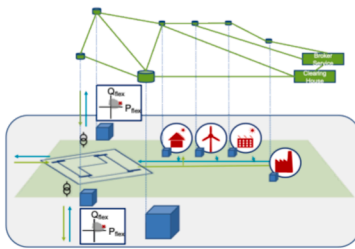
Computation infrastructure for Measurement and model data processing

- Measurement / interface towards grid users incl. model / forecast / controllability
- Measurement / interface towards superordinate and subordinate grid levels incl. model / forecast / flexibility
- Local instance for coordinated autonomous control, automation and operation



Data infrastructure

Distributed data space as part of federated data infrastructure



Communication infrastructure

Communication Infrastructure for autonomous communication

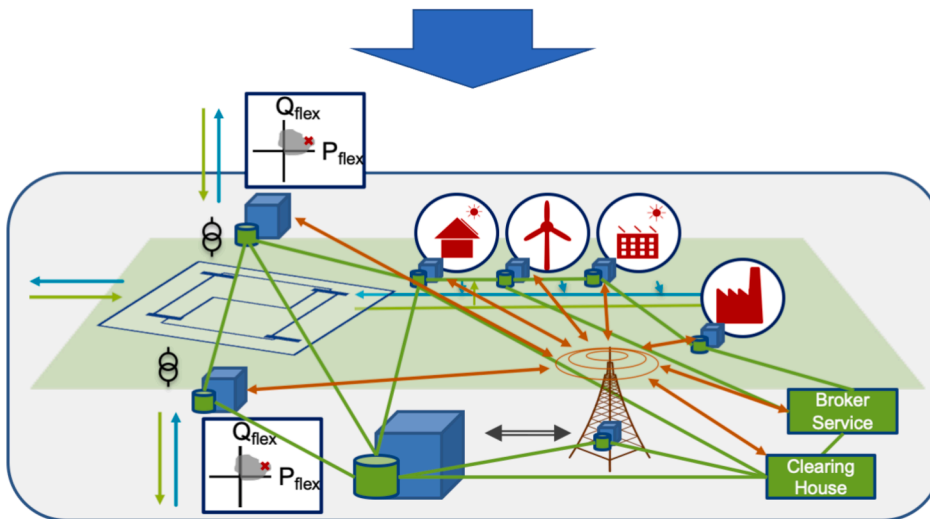
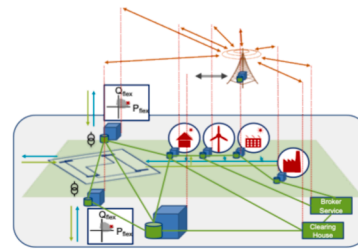


Fig. 3. Required disciplines and perspectives for holonic architecture of power and energy systems.

and data analysis methods promise additional benefits for model creation and algorithms. In addition, the data handling itself will change from large-scale monolithic and centralised databases toward distributed federated cloud-based data handling based on data sovereignty concepts, according to the FAIR data principles [27], i.e. scientific data shall meet the principles of findability, accessibility, interoperability, and reusability.

In summary, the holonic approach proposes to achieve resilience in

future complex power and energy systems and their operation. The holonic structure spans the communication systems architecture, the underlying embedded computing platforms, the supervision, control, and automation algorithms on all levels, as well as distributed data sovereignty concepts for technical and market operation. From the standpoint of various disciplines, holonically distributed data systems can only operate effectively through appropriate communication infrastructures that adopt holonic structures, thereby ensuring resilience.

This principle also applies to distributed computing infrastructures such as embedded systems or edge computing, which facilitate distributed automation and uphold system resilience. Such architectures enable the design and application of power system algorithms for highly automated system operations. It is, therefore, apparent that the individual sub-disciplines and their technical contributions to the overall system are interdependent. They mutually influence each other in order to collectively achieve the goals of resilience and autonomy in power and energy system operation.

3.2. Elements of holonic architectural approaches for power and energy systems in the state-of-the-art

In general, holonic systems feature the following properties, autonomy, cooperation, self-organisation, reconfigurability, functional decomposition, and recursiveness [28]. The difference between holonic, federated, and market-based mechanisms for the coordination of goals of different instances is discussed in [28] for technical sensor grids in automation systems showing the differences between these major approaches.

3.2.1. Fractals and holonic structures and architectures

From a structural perspective, fractals, introduced by B. Mandelbrot [14], are another fundamental approach to analysing complex networks with a hierarchical self-similarity. Fractals are mathematical objects that represent physical systems that show self-similarities and scaling relations. Complex networks in general [29], and electrical networks with their capacitive, inductive, and resonant behavior in particular [30], have been analysed with this approach. Topological similarities and scale-invariant properties regarding eigenvalues of power system dynamics have been presented in [31]. In [32], the fractal approach is tried to represent recursive power grid structures and clusters to allow each substructure to use the same procedure and model. However, it is a fundamental attempt at a structural description without using the mathematical approach of fractals or providing any technical details.

To our best knowledge, the first mention of holons related to energy systems was by [33] in 2007. From the viewpoint of complex systems, which refer to a set of systems that share some common behavioral and structural properties, both the internet and energy markets have been structurally analysed. The results are holonic structures with the aim of applying agent-based methods.

Further, specifically named “holonic architectures” have been developed for the coordination of consumption and later prosumers with the target of energy management of distributed entities. A holonic energy management system for residential areas was published in [34] with the restriction of bundling devices into clusters only on the lowest grid level. The coordination of prosumers in microgrids was presented in [35], and a related Ph.D.-thesis [36] labeled it as a holonic system. The results mainly consist of an agent-based approach for prosumers, which are recursively clustered at various aggregation layers.

However, without relating it explicitly to the holonic approach, the first publication of fully self-organised agent-based coordination of prosumers, including power grid constraints considering the hierarchical structure of the grid, was presented by Wedde et al. in [37,38]. This approach was subsequently further developed to consider real-world regulatory constraints of unbundled and liberalised energy markets and grids [39]. A similar approach is explained in [40] with a holonic approach for local energy markets, although it is restricted to smart buildings and energy-efficient neighborhoods only, while a decentralized optimal reactive power control problem based on a holonic architecture is proposed in [41].

Following the holonic structure, [42] proposes a holonic coordination of production and consumption on different levels of energy systems with a focus on customer satisfaction and quality of service for their energy supply. In [43], the focus is on energy management in microgrids, where information about the flexible micro-macro integration

into larger grid structures is also introduced. Scalability in the sense of application to large numbers of prosumers by splitting the grid into nested management levels is the key idea, while self-management and collaboration with agent-based systems for energy management are considered.

Vlad et al. have attempted to map the IEC 61850 standard, used primarily for sub-station automation, in order to implement holonic structures within substation automation [44]. In [45], the architecture of a prosumer holon is structurally defined with the first implementation within a market and grid structure. However, the approach does not seem to be scalable and follows the traditional implementation concepts. The requirement of autonomy and privacy related to data is mentioned, meaning that the information and authority to make decisions on local issues must stay with each individual local actor. In [46], another holonic active power scheduling approach is presented. A hierarchical energy management system from the EU project e-balance is introduced in [47] and [48], where real-world test implementations in Portugal and the Netherlands primarily based on household devices and Wi-Fi-based coordination are explained. In [49], a broad overview of energy system development towards decentralisation is given. The outlook is on agent-based energy management and mentions the idea of holonic systems as a new trend without any details regarding implementation.

Further holonic approaches for microgrids and energy management of prosumers are presented in [50], with a focus on self-organisation in [51]. A more general approach, where grid users are seen as holons, is described in [52], which bundle themselves into virtual structures like virtual power plants of prosumers. The negotiation about power transfer is the key element here for their organisation.

Recently, [53] described energy management agent (EMA) standards that contain an emerging reference model and its framework architectures. EMA can collect energy demand and autonomously manage energy consumption and generation in energy systems. This is the first standardisation effort toward energy management on the lowest voltage level. 5G is mentioned as a standard industrial communication option in relation to 5G-based IoT. The integration of big data and cloud technologies is mentioned as a target for the future. Another energy management approach on the lowest distribution level for coordination of devices is published in [54]. In [55], an energy management approach with the option to merge and split holons to achieve specific goals and to access the flexibility of active power modulation is described. Flexibility in power systems is a widely used term with varying definitions. However, all centering around the ability to modulate active and reactive power set-points over time, thereby providing needed control power for various purposes [56,57].

In [58], the aspect of balancing active power in city distribution grids for an islanding operation during blackouts is added as a requirement for pure energy management of distributed energy systems. It defines the target of splitting the system into parts and running each part in an islanding operation mode. In a similar direction, the scheduling between microgrids that can flexibly be connected to each other or to an overlay grid can be worked out [59]-[60]. Some kind of flexible islanding operation scheme could be seen in this approach. Specific grid requirements and grid consideration are incorporated only in [61], where the first implementation of an agent-based energy management system for loss reduction and state estimation in distribution grids using a holonic multi-level structure is explained.

Holonic approaches assume a hierarchical system structure, i.e. there are both super- and sub-holons. This fits perfectly for the radially operated networks of primary and secondary distribution. However, in the meshed and interconnected transmission and sub-transmission networks, interactions with neighboring holons on the same hierarchical level must be considered. Furthermore, physical interfaces between holons exist at several locations and exhibit interactions. Both mentioned aspects require a fundamental extension of the holon concept beyond the referenced state-of-the-art system theory of holons, in order to use its advantages on all levels of power and energy systems. This

extension has yet to be fundamentally worked out. Motivating such research work is the purpose of this paper.

3.2.2. Cellular approach for power and energy systems

Whereas most of the above-mentioned references aim for the energy management of prosumers and distributed devices only, there was the fundamental study of the Electrical Engineering society (ETG) of the VDE that proposed the so-called cellular approach for the whole-scale energy system integrating all grid levels [19], i.e. from the extra high-voltage level of the transmission grid down to the low-voltage level of the distribution grid. Local, sub-regional, and regional energy balancing should lead to a minimum of distribution and transmission grid requirements. Based on these ideas, further elaboration and aspects were published in [62] and [63], considering sector coupling and flexibility of grid users. The energy balancing in large-scale systems is simulated for grid planning purposes. Ideas for a related market structure are presented in [64].

In [65], a smart power cell for the interaction between distribution and (sub-) transmission grids was worked out in detail, and a related dynamic simulation framework was created. Both balancing and ancillary services can be demonstrated by this approach. According to the previous definitions, such a smart power cell could be seen as an instance of a holon. Such modeling of cells must be distinguished from microgrids [66] and their autonomous control and economic optimisation [67,68], which only or at least primarily serve themselves. The smart power cell is an instance within the overall hierarchical structure, enabling a functional decomposition. The cellular approach, as presented by VDE, focuses on the power balancing in large-scale power systems down to the low voltage level with a focus on the usage of the electricity grid. Most references related to the holonic approach start from the prosumer level and use types of self-organisation or multi-agent approaches for energy management purposes. Both the holonic and cellular approaches from the references are only structural descriptions that require additional technical solutions for algorithms and communication, data, and computing infrastructures. Their capabilities and benefits shall be enfolded according to the mentioned criteria: autonomy, cooperation, self-organisation, reconfigurability, functional decomposition, and recursiveness.

However, the integration of communication, data, and related computing infrastructure in a similar holonic architectural way is not available in the literature so far. Likewise, the methodical consideration of the power and energy system structure, together with recursively structured power and energy system calculation and operational algorithms, are not considered apart from one first attempt [61]. In addition, the cellular approach focuses on balancing in a sector-integrated manner. However, it has so far ignored other fields of supervision, control, automation, and operation of power systems.

3.2.3. Cyber-physical energy systems, automation and autonomy

Besides the structural organisation discussed above, there is likewise related work regarding cyber-physical energy systems, considering communication, information, and energy systems [69].

A strong trend in research on power and energy system operation is towards automation or even autonomous system operation. Due to the growing complexity of distributed and volatile generation and sector coupling, system operation must be highly automated wherever it is possible. Early results and first approaches for autonomous and highly automated operational processes in relation to multi-agent systems can be found in [70]. An implementation of a distributed coordination of power flow controllers was presented in [71]. A further elaboration of this approach, considering flexibilities from subordinated grid levels and seeing them as self-organised entities or cells delivering services to the superior grid level, is presented in [72] and [73].

Analogue to the autonomous driving of cars [74], a recent study defines the classification of autonomous system operation of energy systems [20]. Requirements for future development of the operation and

digital processes of complex power systems are currently discussed in two task forces of the VDE-ETG [75,78]. The initial results underline the need for autonomous operation of the individual parts of the power system, self-organisation, reconfigurability, and functional decomposition to limit and handle the complexity.

The well-known architecture for Dynamic Monitoring and Decision Systems (DyMonDS) has been proposed as the missing link for establishing workable smart grids [77,78]. To facilitate an orderly, sustainable evolution, DyMonDS provides a means of analytics-supported quantifiable information processing, where the basic intent of the IT is to support decision-making by various entities and interactions among these entities according to well-defined sub-objectives and system-wide objectives. The DyMonDS model focuses on the information exchange framework to align the global objective and the local objectives of various entities within the system. In the simplest form, the global objective of a power system can be considered as a sum of local objectives [79]. The concept has been further refined in [80,81], including validation with real-world grid operation data [82], while a solution where all flexible energy resources are coordinated using a power line carrier frequency signal to follow a preferred demand curve for localized demand control is introduced in [83].

3.2.4. Distributed communication infrastructure for autonomous communication

Distributed communication infrastructures are a key pillar for enabling future defossilized energy systems [84]. This critical role increases with the emergence of distributed automation and, in particular, the proposed holonic architecture. However, in research, the impact of this novel paradigm has so far only been addressed insufficiently [52].

Combined with the overall trend towards increased automation and the target of even autonomous power system operation, the requirements placed on communication solutions rise continuously. Crucial for the safe and reliable operation of such mission-critical applications are resilient, flexible, efficient, and pervasive communication infrastructures. As future energy systems are highly distributed and may even be operated in remote areas, wireless communication, either terrestrial or even satellite, is required to achieve the required ubiquitous coverage. Wireless communications are also ideally suited to allow for flexibility in terms of network topology and scalability from small, autonomous wireless connected holons to full-blown end-to-end connectivity within a large-scale energy system built from many holons. One recent approach to providing exclusive communication resources within public communication networks is the so-called network slicing proposed for 5G. Here, a share of the overall resources is exclusively allocated to the energy system in order to avoid competition with other users in the network. Recent research has shown the feasibility of such approaches and even the resource-efficient dynamic dimensioning of the network slice with the help of machine learning applied to the energy data flow [85]. Yet, public networks are typically not well protected against energy outages, and therefore, network slicing in public networks is primarily a protection of mission-critical services against interference by overload in a fully functional network [86].

Considering the interdependency between energy systems and public communication infrastructure, dedicated communications networks with dedicated energy storage solutions for black-out protection are an alternative way to go. The Federal Network Agency for Electricity, Gas, Telecommunications, Posts, and Railway (BNetzA), the German regulatory body for power and energy systems, has, for example, assigned two radio frequencies at 450 MHz with a bandwidth of only 4.74 MHz each for primary use by critical infrastructures. Similar developments can also be observed in many other countries and have been standardised by the 3GPP consortium [87]. Such new, dedicated cellular networks will serve as an exclusive base communication layer for today's energy system services, such as smart metering or emergency protection measures [88]. Those networks will even function in case of blackouts and, therefore, will provide some minimum communication

capacity still based on LTE to control the energy system in case of crisis. Nevertheless, the spectrum resources reserved for critical infrastructures must be shared with other infrastructures such as water, gas, or heating. Even though the new network as some protection against energy outages, there are still many remaining risks, which may lead to communication outages, such as storms, flooding, cyber-attacks or technical failures. The proposed holonic architecture, therefore, requires new and more resilient communication mechanisms, which allow for autonomous, decentralised communication between holons of the same layer or between different layers of the holonic system. To be most flexible, such new communications mechanisms need to be scalable in terms of resource consumption and highly flexible in terms of topology:

- To achieve efficient usage of the scarce spectrum resources, the predictability of communication demands, as well as the efficient allocation of available channel resources among power system applications and nodes, is critical. This enables an increase in resilience while potentially lowering end-to-end delays by circumventing channel access grant procedures and thus benefiting novel, disaggregated holonic control algorithms [85].
- Another important aspect of the communication infrastructure is its flexible topology. Holons are expected to collaborate but must also be able to operate autonomously. Likewise, the communication must be flexible to react to the circumstances and needs to be aligned with the control algorithms such that both react in a coordinated fashion. Such flexibility has already been brought to communication systems by the concept of Software-Defined Networking (SDN) [89] and Software-Defined Radio (SDR). Recently, the idea of programmable networks has been expanded by the Open RAN (Radio Access Network) concept, which allows for the introduction of real-time micro services via open interfaces [90]. Approaches to take SDN/SDR-concepts to the power domain have been proposed in [86] and [89], but have not been implemented on a large scale yet and also do not yet meet the requirements of future holonic energy systems.

The above-referenced existing works represent just the first steps, and the field of programmable networks and radio interfaces has just started to be explored. To support the concept of a holonic energy system, the idea of a “Multi-X” network of networks as proposed for future, mission-critical 6G networks seems to be an essential approach to be further explored [91]. In “Multi-X” networks, multiple communication options in terms of network technology, spectrum, and protocols are leveraged and combined on a case-by-case basis.

Another promising concept discussed for future 6G networks has been addressed with the keywords “beyond Shannon” and “semantic communications”. Instead of allocating communications resources for “anonymous” bits, application knowledge shall be incorporated into the communication system. This means for the holonic energy system: by considering the actual impact of certain information, such as sensor information generated by the holon, on the energy system, the amount of data to be transmitted can be substantially reduced [92]. Such application knowledge can be created by machine learning for operational data of the energy system as well as system models incorporating expert knowledge about the energy system. The first steps in this direction have been made with the investigations into model-predictive communication for a photovoltaic system, which showed a potential for substantial reduction of the data volume without losing the relevant information [93]. By adopting the concept of transmitting only the “significant” data, a future holonic energy system may benefit from ongoing 6G-related research efforts [94,95].

3.2.5. Distributed computation architecture, embedded systems, edge computing

Power and energy systems represent a major application domain of the Internet of Things (IoT), significantly enhancing the generation,

transmission, distribution, and consumption of electricity and energy in terms of efficiency, reliability, and safety [96]. These systems, particularly complex and resilient autonomous holonic power systems discussed in this paper, require extensive data management and processing. This necessitates multiple computing layers, from embedded devices to cloud servers, to cater to the immense need for storage and processing power. Numerous business factors and challenges associated with adopting cloud computing in power systems, encompassing perspectives from grid operators, utility companies, software vendors, and cloud providers, are discussed in [97]. This enables a range of services, including distributed energy resource management, hybrid simulation, and collaborative system modeling.

Cloud servers, despite their ideal setup for extensive data interchange due to significant network connectivity, face the challenge of geographical distance, leading to potential communication delays not suitable for real-time processing. Thus, edge computing envisions processing the data at the edge close to the embedded devices, where the data is collected, to nullify the induced delay and additionally help data privacy and sovereignty. Offloading decisions between edge and cloud remains a major challenge as it depends on multiple parameters, factors, and optimisation criteria. In [98], an architecture is proposed that shifts away from cloud-centric models, focusing instead on a microgrid controlled and managed through an edge-embedded system. This allows for local management and communication with other smart grid components, such as utility suppliers, while the cloud serves as the host for the information management system.

Processing units include microcontroller units by default and can be extended to systems-of-systems to provide higher computational capabilities on the edge by incorporating hardware accelerators, digital signal processing, etc. A survey about hardware and software architectures for edge processing platforms, in which data acquisition, data processing, data storage, and data transmission are considered, is presented in [99]. Hardware design solutions may integrate on-chip MEMS technology solutions for on-chip compressed sensing together with integrated radio transceivers for multi-radio connectivity on the chip. The design flow for such integrated SoCs is more complex as verification and debugging of mixed-signal system-of-systems considering connectivity capabilities needed for the communication using RF interfaces is required. Support for Electronic Design Automation (EDA) tools to ease hardware design, verification and validation is crucial. A detailed survey of design automation approaches for efficient and robust electrical grids in smart buildings where control, communication, and computing subsystems must co-exist is presented in [100]. An emphasis is made on the necessity for the co-design of control algorithms and embedded platforms, as various aspects of the platform, including sensor accuracy and availability, communication channel reliability, and computing power of embedded processors, may have a significant impact on the quality of developed distributed control algorithms. Different distributed control algorithms can then be chosen depending on the different sensing and prediction accuracy capabilities of the embedded platforms.

Several custom embedded systems solutions have been proposed for power management, for example, in [101], in which a co-emulation framework on FPGA-based Multi-Processor System-on-Chip (MPSoC) hardware, considering both the electromagnetic real-time transient power system executed on programmable hardware units together with communication using physical hardware layer and network ports. System monitoring and control applications are executed within the soft processors of FPGA-MPSoCs. Another example of customised embedded hardware design considering on-chip power delivery systems for load balancing is presented by [102], where under-provisioned on-chip voltage regulators are interconnected by switch-networks. The goal is to reconfigure the power delivery network on the chip by combining the output of multiple voltage regulators whenever the workload demand exceeds the peak current rating of a single regulator. However, a unified edge platform solution considering the requirements of future complex and smart power systems is still missing. Moreover, to support

distributed and hierarchical algorithms for the management and control of holons, requirements on resilience, dependability and timing should be guaranteed by the platform in an End-to-End (E2E) fashion over the entire Device-Edge-Cloud-Continuum. Today, no formal framework exists for guaranteeing services for practical systems spanning embedded devices, (wireless) communication, and (edge) clouds, mainly due to the heterogeneity of involved resources and their scheduling and resource management policies [103].

The requirements for supporting autonomous systems are also shifted to embedded platforms. Approaches in [104] propose to support self-awareness in MPSoCs, thereby improving the behavior of highly parallel and heterogeneous embedded platforms. The goal is for MPSoCs to have a better understanding of their own state, their behavior, their performance and their surrounding conditions, making them more robust and reducing processing and communication requirements. This design is augmented with a supervisory control layer for configuring different adaptive control policies based on the state of the system. An application of self-awareness in autonomous systems to an Information Processing Factory (IFP) is presented in [105]. Further designs with an emphasis on required distributed infrastructures for autonomy supporting safety at design and operational time have been proposed in [106] and provide fundamental approaches for the holonic approach.

Despite these advancements, there are still significant challenges in the development of an autonomous systems platform supporting the holonic architecture. These include establishing correctness in case of misbehavior, operational validation of adaptively smart systems, and analysing the trade-offs in smartness features. Addressing these challenges is crucial for the progression of autonomous systems platforms.

3.2.6. Distributed data space as part of federated data infrastructure/data sovereignty concepts

Data spaces enable demand-driven data sharing in a scalable and sovereign way. The term is used from different perspectives with varying emphases. From a business viewpoint, the term is often used colloquially for a collection of data processing services from various stakeholders and, more precisely, as an alliance of organisations that pursue common data-sharing goals and face similar challenges, which motivates them to join forces in tackling the challenges by defining governance and technologies as well as provide essential services for data sharing. Data spaces are part of the European Data Strategy, which envisions a vivid data economy for the benefit of society as a whole, realised by increased sharing of data while keeping individuals and organisations in control of their data [107]. In different existing and upcoming regulations, data spaces are obliged to comply with regulations [108,109,110].

As data space technologies manage intrinsically uncertain business relationships [111], they fulfill the demands for flexible data sharing in a dynamic business environment that requires ad-hoc integration instead of long-term integration artifacts or static communication channels [112]. In particular, business ecosystems benefit from data space technologies as they are characterised by loosely coupled relationships between members [113]. Data spaces are a basis for data ecosystems, where the monetarised, exchanged, and stand-alone asset is data [114], considering all their particular characteristics and potentials [115].

From a technology perspective, data spaces present a distributed data integration concept. In contrast to a traditional data management system, data space systems provide an additional set of services and an abstraction layer that aggregates over the participant system [116,117]. They are characterised by semantic data integration using linked data principles instead of physical data integration, remain a decentral data holding, enable overlaps and nesting [117,118].

The data space concept thus connects two approaches and deploys their benefits: Firstly, it uses networks as an organising principle and semantically connects data sets, as emphasised in the linked data community [119]. Secondly, it applies services that hold capabilities for data sovereignty and ensure complete control over data [120].

The software services required for data spaces go beyond the direct

data processing services as data spaces require support services that are “essential for managing” the data space and deal with metadata and information for data sharing as well as participant organisation [116]. These essential services constituted by a software system and common agreements recently gained attention as software infrastructure or soft infrastructure for data sharing [121,122]. They describe standardised agreements for intangible, robust, and build-on convergence structures that facilitate data-sharing ecosystems in an infrastructural manner. Infrastructures are characterised by six key aspects: enabling, shared, open, heterogeneous, having an installed base, and being socio-technical [123]. These characteristics apply to digital infrastructures in general as “the basic information technologies and organisational structures, along with the related services and facilities necessary [...]” [124], and data sharing infrastructures in particular. Data platforms and “data infrastructure as a platform” recently gained attention in research and practice due to their capabilities and tools for dynamically and efficiently leveraging crucial data as a resource that is required for relevant use-cases [125,126]. They reflect the close relationship between platforms and infrastructures [127].

The essential services and agreements that enable the integration of decentralised databases make data spaces a federated system. Federation is recognised as a key principle for realising sovereign data sharing on a peer-to-peer basis between participants [120,128]. This means that only metadata and additional information necessary for data sharing are organised via federation mechanisms, and the actual data is exchanged between the participants themselves. A federation is a form of distribution that originally referred to databases [129] but also described complete information systems [130]. A federated system balances two fundamentally conflicting demands by enabling “a reasonable degree of information sharing” and the autonomy of its components, or in this case, databases [131]. They are characterised by physical distribution, heterogeneity, and operational independence up to a different extent [130].

This implies challenges that are addressed by data space systems: A central authority is replaced by a cooperative activity and agreed-upon protocols, the participant components must be enabled to specify the data to be made available and its terms, and federations must be able to create their own schemes to meet their needs, and participants should be able to dynamically enter or leave the federations. The necessity of uniting communication and sharing mechanisms is an opposing force, for example, the ability to negotiate and agree upon data usage contracts [131].

The federated architecture of data space is discussed with regard to future developments towards a more decentralised approach without any central authority or enabling service structure. Complete decentralised data storage goes a step further and is based on distributed ledger technologies as well as decentralised applications. They emerge for decentral technologies and data sharing but also for a decentralised digital economy [132,133].

To realise the benefits of decentralised structures, decentralisation can also be introduced in the design and application architecture of the essential service components in contrast to a complete data space architecture. The services can be designed in a decentralised manner and use decentralised computing power mechanisms [134] or identification methods [135]. This strong research trend will be taken up for its demonstration within the holonic architecture for power and energy systems.

Using and developing data spaces for our holonic structure presents several challenges. Currently, a policy management system for a holonic structure does not exist. The tracking of data, the terms of use for data, and the enforcement of these terms at the recipient’s end need to be addressed. Up to now, data spaces have been utilised by independent partners but not for interconnected holons. Moreover, the focus of data spaces has primarily been on data exchange. However, in our holonic system, we are dealing with data-to-compute and compute-to-data scenarios. Additionally, federated learning and split learning scenarios for

real-time cooperation and control have not yet been integrated into data spaces. Another open question is how we can ensure that a data exchange has actually occurred. Further focus has to be given to improve the resilience of the electrical grid by identifying anomalies and detecting cyber-attacks. A detailed description of the cyber-physical power system testbeds to identify cyber-attacks and their architecture is explained in [136,137]. Machine learning can also be used to identify false data, as explained in [138].

3.2.7. Summary on the state-of-the-art of holonic architectures and related disciplines

In conclusion, it can be stated that in all addressed research areas like power and energy systems, communication, computation and data, fundamentally new solutions are necessary to enable the overall holonic architecture for power and energy system automation and operation. The latest research trends will be either set or taken up to mutual benefit for addressing the overall holonic architecture.

The state-of-the-art does not provide appropriate solutions in terms of algorithms and technologies to fulfill the requirements of the holonic approach. Today's algorithms and methods for power system management and system operation cannot be executed in a distributed manner for subsystems in interaction with other systems as scalability is not given. The current state-of-the-art requires centralised model structures and complete, i.e. flawless, system descriptions of all considered grid levels. Commercial communication systems also make use of central organisation and coordination instances that create dependencies on higher network levels. Specific communication systems for subsystems, on the other hand, would be inefficient and would not achieve the necessary system-level robustness in the holonic sense, combining all structures and underlying hardware and software infrastructure. Methods for distributed secure data management that take data sovereignty into account are only in their infancy, particularly in power and energy systems. Distributed computer infrastructures, which enable the redundant and migratable execution of encapsulated functions in the event of a failure, need to be further driven towards the holonic architecture requirements. Securely executing distributed functions, even in the event of failure of individual computing nodes or communication links, goes far beyond the existing state-of-the-art.

4. Building blocks for holonic structures

The following three case-studies of current research results illustrate how crucial building blocks for creating holonic structures in the control, communication and computation layers of an emerging future smart power and energy system are coming into being. These three case-studies showcase in the following:

1. Versatile ICT infrastructure that is industrially scalable and whose actual functionality is context-dependent, i.e. software-defined power system control and protection functionalities;
2. Digital Twin modelling concepts that allow for holonic system modelling;
3. Flexibility modeling, assessment and aggregation that allows effective flexibility provision in holonic power systems.

4.1. Distribution grid automation based on versatile grid edge devices with software-defined functionality

Following the holonic approach, distributed edge devices are intended to undertake the largely automated monitoring, control, and operation of parts of the network, i.e. sub-grids. To this end, edge devices are installed, for instance, in secondary substations, which collect local grid measurements from the medium and low voltage levels and, potentially, also serve as actuators. By exchanging this data and linking it with grid data and additional information about the connected facilities, the

network state at the medium voltage level can be determined. The same can be achieved for the low-voltage level by including, for example, smart meter data or by communicating with facility controls, like EV chargers or RES, on that level. If the operational boundaries in the network, such as voltage or power flow limits, are violated, control actions can be taken. Fig. 4 shows the basic distribution of such edge devices in an exemplary medium-voltage network with an underlying low-voltage network.

According to the holonic approach, the communication between the devices must be executed in such a way that it can operate locally without a central entity. For example, the 5G mobile communication standard allows stand-alone local communication within a radio cell, even if the cell is not connected to a central communication system. Thus, this holonic requirement could be fulfilled or rather implemented using already existing communication standards.

The measured data are redundantly stored in a distributed database. To determine the network state at the medium voltage level, the necessary data for state estimation, including the topology, are collected in an edge device. Network and topology data must be stored locally but can be checked and validated using local information.

If an edge device fails, part of the system information is missing. According to the holonic approach, another edge device must take over the function, which means that the process must be migrated there. Due to the distributed data approach, the necessary information remains retrievable. However, the data from the failed device must be estimated so that a fail-safe mode is reached. A state estimation may be less accurate, but it is still executable within certain limits. These properties of fail-safe and fallback security must also be implemented for all further functions.

The local data can be transmitted to a central operation centre with a Man-Machine-Interface (MMI), as desired. Here, disturbances in the network that cannot be resolved locally by automation are reported and displayed. Apart from operational monitoring, this central entity primarily serves the configuration and parameterisation of decentralised devices. The digital twin of the entire system, consisting of network and secondary technology, is matched here (Section 4). If the operation centre is implemented as a cloud-based entity, it can access the distributed data, and the information is also available elsewhere in the system.

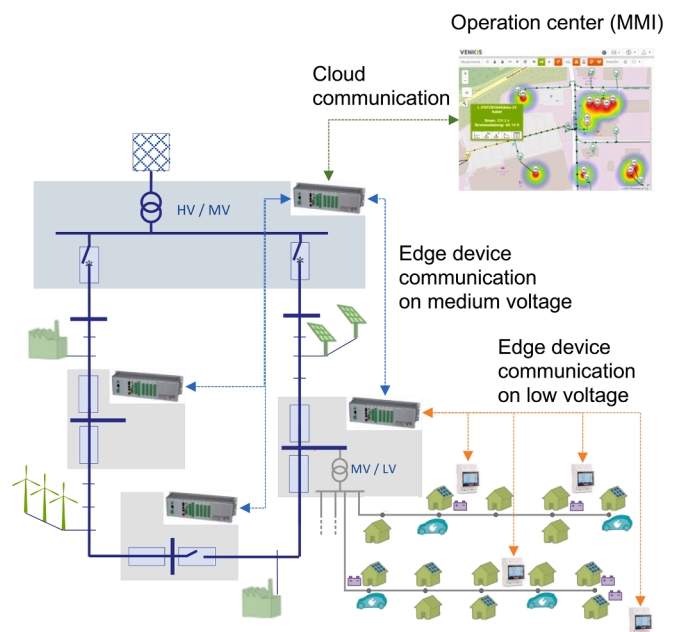


Fig. 4. Medium and low voltage grids equipped with edge computing devices for supervision, operation, and control.

With this architecture of distributed edge devices, a wide range of functionalities can be executed. These include, for example:

- Monitoring functions
 - State Estimation
 - Power Quality Monitoring
 - PMU
 - Topology detection, identification and validation
- Smart Grid functions
 - Congestion management by RES/load flexibility
 - Optimisation, e.g., Optimal Power Flow (OPF) / Model Predictive Control (MPC)
 - System-wide voltage control (Q(U))
 - Topology optimisation (MV- and LV topology switching/shifting of grid separation points)
- Protection functions
 - Various protection functions
 - Fault direction indication

Such a multitude of functions can only be meaningfully mapped if modular functions can be implemented on one device rather than having separate devices for individual functions. To achieve this, separation should be made into standardised, powerful hardware, which is installed once, and modular software functions, which can be expanded and adjusted later on. These software functions, for instance, can be encapsulated using container technology, allowing them potentially to be used on other hardware platforms. The description of the entire system must be standardised so that the configuration of the devices and the engineering can be executed independently of the hardware. For this purpose, IEC 61850-6 [139] is suitable as an established substation automation standard. An integrated engineering process based on System Configuration description Language (SCL) accesses a pool of smart grid functions. The SCL data model defines which functions are active. The selection of functions is driven via standard SCL engineering tools. Furthermore, the SCL defines relations and communication between devices and functions. Based on the standardised system description using SCL, test routines can also be executed [140]. The ideas have been experimentally verified as part of laboratory experiments [141,142] and field tests [143].

Fig. 5 exemplifies such an edge device in a secondary substation. All the measurements are collected via distributed Analog-Digital (A/D)-

units and transmitted via a real-time protocol to the main unit. Alternatively, they are collected as analog values in the central unit. Due to a high sampling rate and suitable filtering, the measurements should also be used for protection functions as well as power quality up to 10 kHz. With additional time synchronisation, a synchrophasor (PMU) measurement is also conceivable. Additional low voltage measurements should be digitally provided per feeder through a bus protocol like Modbus, for example. The system should possess suitable processors that suit real-time and protection applications.

The benefits of automated monitoring of medium and low voltage networks, together with bottleneck management, voltage regulation, and system optimisation, are that it avoids the necessary grid expansion, which is conditioned by new loads such as electric vehicles or RES. The mere observation of the actual grid status alone, e.g. in the form of low-voltage grid monitoring, can already allow higher grid loads compared to traditional conservative grid planning approaches. For further grid load, rare interventions into load or feed-in flexibilities must be considered. Thus, rare cases of higher simultaneity can be dealt with without having to expand the grid. Overall, it must be noted that the load and feed-in flexibilities are increasingly needed for the overarching market, which compensates for the volatile renewable energies, such as large onshore and offshore wind parks, in the overall system. If a simultaneous load ramp-up occurs due to low electricity prices during high RES surplus production, the distribution grids will be heavily loaded. This would be a smart market situation against which the smart grid operation, i.e., the monitoring of the grid and possibly limiting load peaks from very high price-induced simultaneity factors, must be weighed. This example illustrates how the holonic approach of distributed grid monitoring helps coordinate the interaction of the different grid levels.

4.2. Digital twins supporting the holonic architecture

Establishing a holonic architecture with distributed computational devices and algorithms necessitates rigorous data management for both system modelling and function description. The processes of network planning, asset management, and system operation are closely interconnected. The same data is needed in various forms throughout these processes. The concept of digital twins provides the basic idea that data is collected only once and then utilised for all processes over the lifespan of a device, a feature referred to as life cycle capability. In this context,

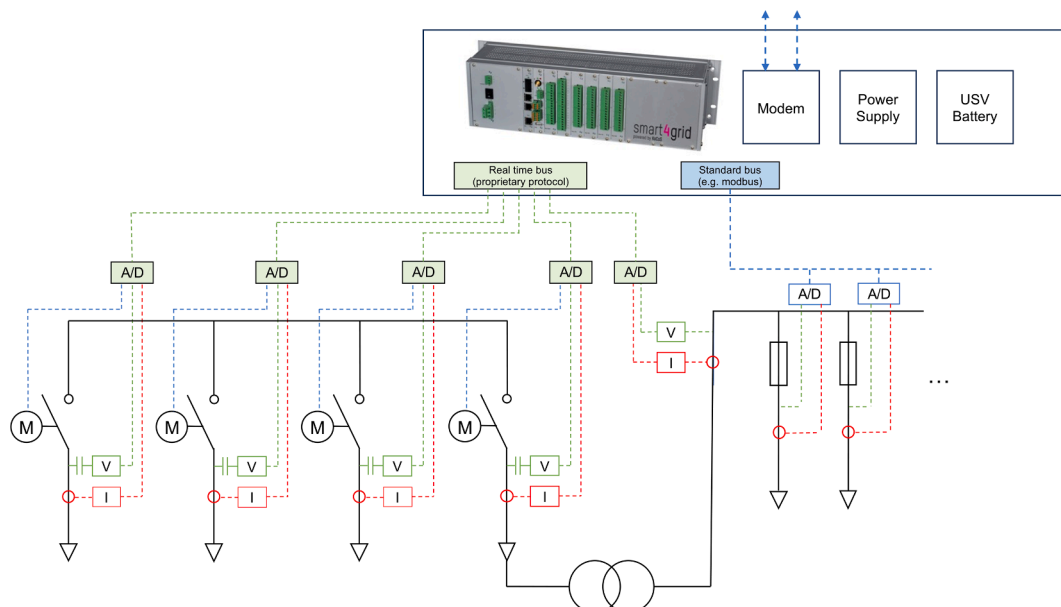


Fig. 5. Edge computing device for smart grids integrated within a secondary substation.

data adheres to the single-source-of-truth concept. Strict object orientation allows for the addition of supplementary information, enabling its use in different processes.

Fig. 6 schematically illustrates the essential process steps from network operation, asset management, as well as the configuration and operation of the distributed devices like the edge devices of the holonic architecture. A dataset of the network used for planning should also form the basis for the asset management data. From this, the necessary monitoring, control and operation functions for the holonic system are determined during engineering of the control system including ICT-setup. Likewise, the data serves the configuration of functions, for instance, network data needed for state estimation. In the operation centre, the expected measurement values are created using this data. Also, if there is a consistent digital twin-based process, this should run in a completely data-driven and automated way. The decision about which information from this is forwarded to a higher-level control centre is a specification during engineering.

The value of a unified data and application model also becomes apparent when we consider the backward arrows in Fig. 6. The data and information from the operation of the edge devices, as well as those aggregated at the operation centre, provide valuable insights for asset management and network planning. The loading of devices can be directly derived from the operation information and can validate the planning assumptions.

From an implementation perspective, the cloud-based operation centre can also serve jointly as a platform for engineering and configuration. Decisions must be made about how the data of the digital twin are ultimately generated and maintained, but these should be derived from one single instance in the system and not newly created or entered at different instances. Thus, it could be demonstrated that the digital twin ultimately establishes certain paradigms for data handling, which support the implementation of a distributed holonic system.

Fig. 7 displays an exemplary use case in which a digital twin of a low-voltage distribution grid operating on an embedded system in a digital local substation is generated and can support the aforementioned planning, management and operation of the respective low-voltage holon. The digital twin operates the holon “low voltage grid” autonomously while being able to communicate to adjacent or superior holons as well as a cloud-based distribution grid control centre using publish-subscribe or client-server-based machine-to-machine communication protocols. At the top of Fig. 7, existing data sources at Distribution System Operators (DSOs), such as Geographical Information Systems (GIS) or Asset Management (AM) data, which represent the actual grid, are mapped to a standardised and exchangeable power system grid model. In the given example, the standard CIM CGMES grid model format according to the norm IEC 61970 is used [144].

Selected parts of the standardised grid model are subsequently used to generate the edge digital twin. The digital twin consists of digital representations of the individual components of the holon, labelled as digital shadows, a power system model and data platform, a distributed database and different smart grid or smart market functions, all

components encapsulated in software containers. Digital shadows are defined in [145] as the digital representation of an object receiving information from the physical device. The different functions are deployed by the cloud-based control centre. The control centre of the DSO is responsible for the supervision and maintenance of the digital twin and receives operational data from the digital twin. This data is fed back to the standardised grid model, enabling the DSO to use it for further applications such as, but not limited to, grid planning and asset management. At last, the digital twin is able to communicate with the holon of the medium voltage grid displayed at the bottom right of Fig. 7 to exchange data required for the operation of the medium voltage holon.

4.3. Flexibility Modeling, Assessment, and aggregation in holonic power systems

Operational flexibility in power systems is increasingly needed for coping with the growing uncertainties in power system operation. This is due to rising shares of intermittent RES generation but also due to the increasing degree of sector coupling, involving comparatively high-powered units such as Electric Vehicle (EV) chargers and Heat Pumps (HPs). Besides maintaining the total balance between power generation and consumption, flexibility will be used to mitigate local and regional grid congestions.

The coordination of flexibilities requires modelling the flexibility potential and determining the flexibility demand within a given power system. System studies provide insights into the potential infrastructure savings through the inclusion of flexibilities in power system operational processes. Due to the hierarchical nature of power systems and operating entities such as Transmission System Operators (TSOs), Distribution System Operators (DSOs), utilities and customers, alongside the large number of small-scale generation and storage units, aggregation of information has been heavily investigated for future operational concepts. Rather than between voltage levels, which present natural interfaces in the power system, the major focus has been on interfaces between TSOs and DSOs [147]–[148].

Modelling operational flexibility in abstracted ways is a very active research stream [149]. Different approaches have been identified to describe the flexibility potential of individual Flexibility Providing Units (FPUs), including EVs, BESSs, RESs and HPs, all based on algebraic descriptions of unit constraints and mathematical optimisation, using for instance flexibility cubes [150], the PQ-domain as well as its time-dependent extension, the PQ-t domain, in Fig. 8. The majority of related research work identifies the flexibility potential of FPUs in the PQ-domain, that is, considering interdependencies between simultaneous active and reactive power flexibility with detailed modelling of converter characteristics [151–159].

Modelling, assessing and tapping into available and *vice-versa* needed flexibility from FPUs and aggregating flexibility from FPU pools is becoming an essential and oftentimes also mandatory process in day-to-day power system operation, confer for instance to the recently introduced *Redispatch 2.0*, previously mentioned in Section 2.1, process that

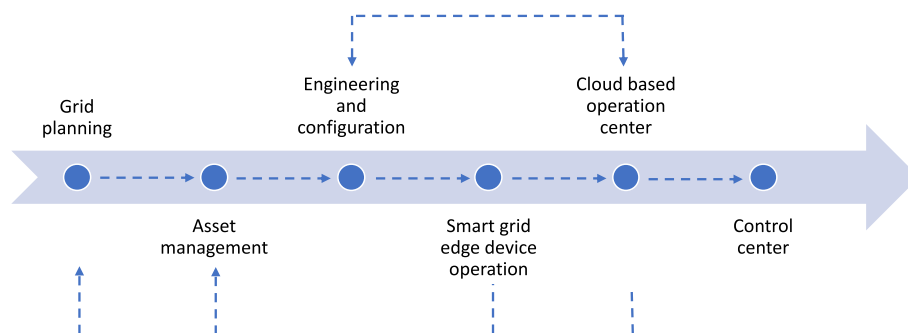


Fig. 6. Sequence of use cases of a digital twin for grid planning and operation.

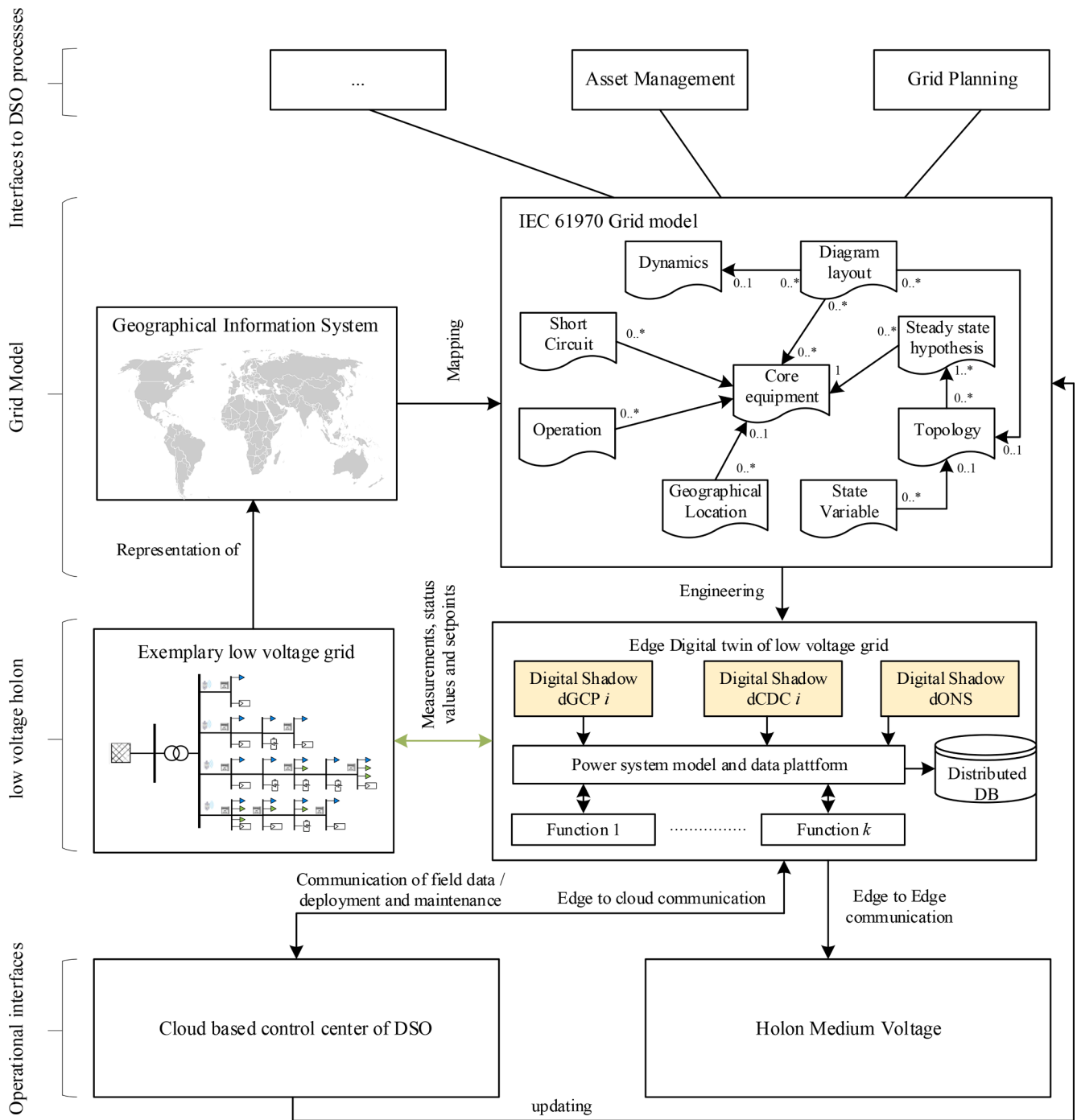


Fig. 7. Exemplary use case of a digital twin in a low voltage distribution grid operating on an embedded system [146].

shall assess and control all flexible generation and storage units above 100 kW, which is currently becoming mandatory for German DSOs [16] and will likely be extended to even smaller DER units [18].

Aggregation of operational flexibility from subsystems also allows to abstract away from individual power system units or FPU, the parts or sub-holons, and their respective individual operational state and technical limitations to an aggregated flexibility, a virtual FPU, the whole or super-holon, with an ideally identical, i.e. self-similar, representation of the available flexibility of the FPU pool. This modeling and abstraction of flexibility representation is also key to overcome the otherwise cumbersome and limiting complexity of dealing with many FPUs, i.e. potentially thousands of individual flexibility providing units, all at once.

Flexibility aggregation is, as shown in Fig. 9, at the centre of hierarchical Flexibility Coordination Schemes (FCSs), where flexibilities of FPU pools are presented as virtual flexibilities at the internal system boundaries, such as between different grid operators or voltage levels.

While the process of flexibility aggregation is required to model the available virtual flexibility of an FPU pool, the process of flexibility disaggregation is needed, when actually distributing flexibility provision from the FPU pool to the underlying individual FPUs. As shown in Fig. 10, an intuitive way for representing flexibilities is in the form of abstracted storage units that can provide or absorb power over time, subject to some internal power and energy constraints. This also shows in a neat form the self-similarity of lower-level flexibility aggregators, i.e. sub-holons, to higher-level flexibility aggregators, i.e. super-holons.

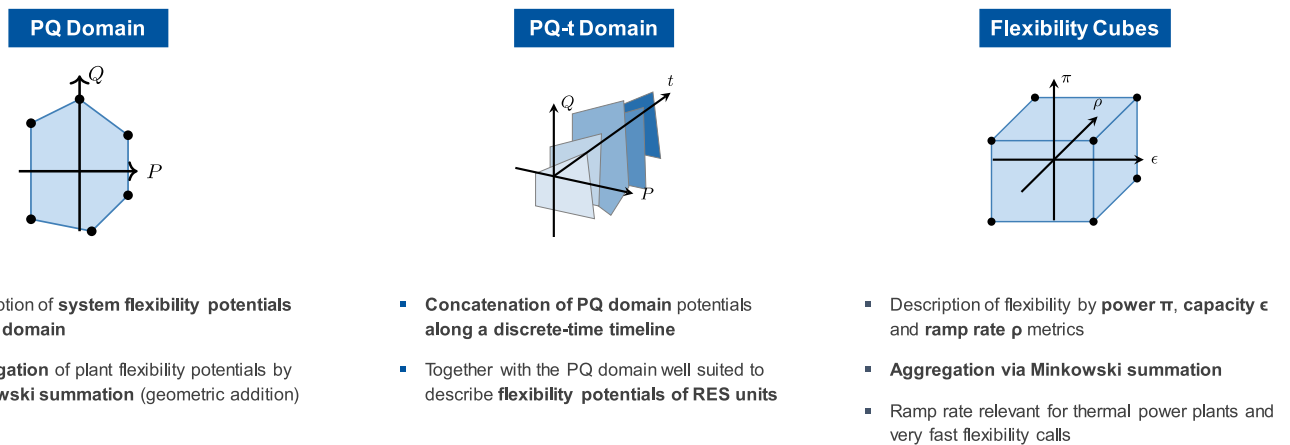


Fig. 8. Illustration of different forms of graphical representations for operational flexibility [157].

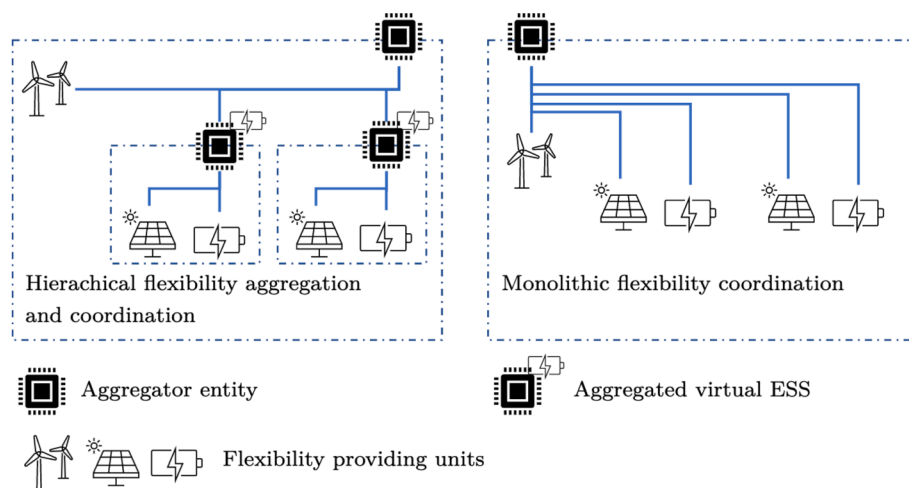


Fig. 9. Hierarchical and monolithic Flexibility Coordination Schemes (FCSs) [158,159]. Intermediate aggregator entities combine underlying flexibilities into virtual flexibilities in hierarchical FCSs.

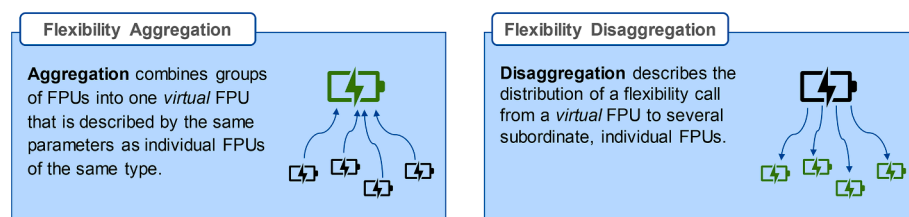


Fig. 10. Aggregation and disaggregation of operational flexibility [157]. Left: Aggregation of available flexibility from an FPU pool into the form of a virtual storage unit. Right: Disaggregation of requested flexibility delivery from the virtual storage unit to the individual FPUs.

For the consideration of distributed flexibility in simulations and optimisations of superimposed voltage levels, e.g. the transmission grid, aggregation reduces the computational complexity when the underlying FPUs are used for their operational flexibility. However, issues of flexibility assessment accuracy as well as information loss when either abstracting from individual FPUs with their potentially nonlinear behaviour or when aggregating a pool of heterogeneous FPUs into one virtual FPU are manifold. Addressing and solving these issues is ongoing research work [157].

5. Conclusions

The future operation and control systems for increasingly distributed

power and energy systems requires an increasing degree of automation. Following the decentralisation of the primary technical system, i.e. the energy generation and storage units, the secondary technology, i.e. the ICT layer comprised of sensors, actuators as well as communication and computation, must also be able to monitor, automate, and operate the system in a decentralised and robust manner to ensure the overall system's resilience. However, the current state-of-art of power and energy systems operation is addressing these issues in a non-holistic fashion, e.g., control and automation solutions are discussed without considering the changes required in the underlying ICT infrastructure. To address this continuously widening gap, this paper has proposed the concept of holic design principles and architectures for power systems.

This paper has conceptually discussed how to design computer,

communication, and data infrastructures in a decentralised manner such that in the event of disturbances and failures, only as small a part of the system as possible fails. Such an architecture offers the possibility that subsystems can be detached from the overall interconnected system at any time and continue to operate as island networks, provided the corresponding control algorithms are implemented following the holonic design principles of autonomy, cooperation, self-organisation, reconfigurability, functional decomposition, and recursiveness within the part-whole structure of the holonic system-of-systems approach.

In the show-case section, a first implementation example of software-defined, versatile-in-use distribution network automation hardware, which meets the requirements of the holonic architecture, was shown. A second show-case presented the digital twin modelling approach as a specific type of process structuring and data management, which is amenable to holonic systems. A third show-case presented a modeling, aggregation and coordination scheme of flexibility in holonic grid operation.

The crucial prospect of the proposed holonic architectures is that it combines aspects of (functional) similarity (cf. fractal architectures) with the possibility to allow for considerable heterogeneity of subsystems (cf. multi-agent systems) and with a system-of-systems approach. At the same time, the holonic approach explicitly takes the enabling underlying ICT infrastructure into account. We argue that the current state-of-the-art does not offer any concept of similar applicability.

The here presented holonic design concept and holonic systems structures are presently still a research vision, yet sufficiently ambitious to go far beyond existing control, operation and coordination schemes, such as multi-agent systems. We believe that control, communication and computation in highly distributed and complex infrastructures like the electricity grid have to be thought of in a truly holistic sense and that the created system architectures need to reflect this, while achieving resilience through purposeful self-autonomy of the whole system as well as adequately proportioned sub-systems.

In the on-going energy transition, the rate of change in power systems is accelerating fast such that incremental changes and adaptations to current power system structures might likely not suffice to be successful solutions in the long run, i.e. when approaching 100 % RES generation with large shares of storage capacity and in principle flexible load demand. For this audacious new design paradigms such as the holonic design concept are needed.

CRedit authorship contribution statement

Christian Rehtanz: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Andreas Ulbig:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Rajkumar Palaniappan:** Writing – review & editing, Writing – original draft, Conceptualization. **Timm Faulwasser:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Selma Saidi:** Writing – original draft, Conceptualization. **Anke Schmeink:** Writing – original draft, Methodology, Conceptualization. **Christian Wietfeld:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This paper is based on the keynote speech of Christian Rehtanz at the IEEE Powertech 2023 Conference in Belgrade, Serbia, on 27 June 2023. The results in Section 3 were supported by the German Federal Ministry for Economic Affairs and Climate Action [grant number 03EI6001A]. The results in the other sections did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements are given to the following colleagues contributing with ideas and material: Peter Buchholz^a, Jian-Jia Chen^a, Martin Grohe^b, Ulf Häger^a, Thomas Offergeld^b, Maria Kateri^b, Antonello Monti^b, Albert Moser^b, Boris Otto^a, Fendinanda Ponci^b, Thomas Schwierz^a, Alfio Spina^a and Klaus Wehrle^b (^a TU Dortmund University, ^b RWTH Aachen University). Acknowledgements are also given to the reviewers for their helpful comments and suggestions.

References

- [1] International Energy Agency (IEA), "Renewables 2023: Analysis and forecast to 2028," Paris, France, January 2024. URL: <https://www.iea.org/reports/renewables-2023>.
- [2] International Energy Agency (IEA), "Electricity Grids and Secure Energy Transitions," Paris, France, October 2023. URL: <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions>.
- [3] E. Veldman, M. Gibescu, J. G. Slootweg and W. L. Kling, "Technical benefits of distributed storage and load management in distribution grids", 2009 IEEE Bucharest PowerTech, Bucharest, Romania, 2009, 10.1109/PTC.2009.5282092.
- [4] Strbac G, Kirschen DS, Moreno R. "Reliability standards for the operation and planning of future electricity networks." Now Foundations and Trends 2016. <https://doi.org/10.1561/3100000001>.
- [5] F. Milano, F. Dörfler, G. Hug, D. J. Hill and G. Verbič, "Foundations and Challenges of Low-Inertia Systems (Invited Paper)," 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 2018, 10.23919/PSCC.2018.8450880.
- [6] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems", 2013 IEEE Power & Energy Society General Meeting, July 2013.
- [7] Dvorkin Y, Kirschen DS, Ortega-Vazquez MA. Assessing flexibility requirements in power systems. IET Gener Transm Distrib 2014;8(11):1820–30.
- [8] Heylen E, Deconinck G, Van Hertem D. Review and classification of reliability indicators for power systems with a high share of renewable energy sources. Renew Sustain Energy Rev 2018;97:554–68.
- [9] J. A. P. Lopes, A. G. Madureira, M. Matos et al., "The future of power systems: Challenges, trends, and upcoming paradigms," Wiley Interdisciplinary Reviews: Energy and Environment, Vol. 9, Issue 3, 2020.
- [10] D. K. Molzahn, F. Dörfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick and J. Lavaei, "A survey of distributed optimization and control algorithms for electric power systems," IEEE Transactions on Smart Grid, Vol. 8, Iss. 6, p. 2941-2962, 2017.
- [11] J. M. Guerrero, M. Chandorkar, T. L. Lee and P. C. Loh, "Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control," IEEE Transactions on Industrial Electronics, Vol. 60, Iss. 4, p. 1254-1262, 2012.
- [12] M. Braun, J. Brombach, C. Hachmann, D. Lafferte, A. Klingmann, W. Heckmann et al., "The Future of Power System Restoration: Using Distributed Energy Resources as a Force to Get Back Online", IEEE Power and Energy Magazine, Vol. 16, Iss. 6, pp. 30–41, 2018.
- [13] Koestler A. "The ghost in the machine", The Macmillan Company. N Y 1968. <https://doi.org/10.1126/science.160.3828.649>.
- [14] B. Mandelbrot: "Fractals: form, chance, and dimension", Verlag W.H. Freeman, San Francisco, 1977, 10.1063/1.2995555.
- [15] Bundesnetzagentur (German Grid Regulator), English Website, URL: <https://www.smard.de/en>, Last accessed: July 28, 2024.
- [16] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., "BDEW Branchenlösung Redispatch 2.0," 2020. URL: <https://www.bdew.de/service/anwendungshilfen/bdew-branchenloesung-redispatch-20/>.
- [17] F. Salm, M. Oettmeier and P. Rönsch, "The new redispatch and the impact on energy management in districts," 2022 18th International Conference on the European Energy Market (EEM), Ljubljana, Slovenia, 2022, 10.1109/EEM54602.2022.9921014.
- [18] C. Krueger, M. Otte, S. Holly, S. Rathjen, A. Wellssow and S. Lehnhoff, "Redispatch 3.0 – Congestion Management for German Power Grids – Considering Controllable Resources in Low-Voltage Grids," ETG Congress 2023, Kassel, Germany, 2023.
- [19] VDE. The cellular approach – The basis of successful, cross-regional energy transition. VDE-Study 2015. <https://shop.vde.com/de/vde-studie-der-zellulare-ansatz-2>.
- [20] M. Braun, M. Lindner, C. Rehtanz et al., "Systematisation of autonomy levels in network operation management," ETG Journal, 2020, URL: <https://www.vde.com/resource/blob/1979462/a73e5c5f684abdc94ba63b03232b00d5/impulse-paper-automation-power-grid-operation-data.pdf>.

- [21] A. G. Givisiez, P. Kyriacos and L. F. Ochoa, "A review on TSO-DSO coordination models and solution techniques," *Electric Power Systems Research*, Vol. 189, Iss. 106659, 2020.
- [22] Top P, Bell MR, Coyle E, Wasynczuk O. Observing the Power Grid: Working Toward a More Intelligent, Efficient, and Reliable Smart Grid with Increasing User Visibility. *IEEE Signal Process Mag* Sept. 2012;29(5):24–32. <https://doi.org/10.1109/MSP.2012.2186763>.
- [23] Strachan A, Elders I, Galloway S. "Improving Network Visibility for Better Integration of Low Carbon Technologies into LV Networks," 53rd International Universities Power Engineering Conference (UPEC), Glasgow, UK 2018. <https://doi.org/10.1109/UPEC.2018.8542016>.
- [24] Zhang YYC, Feng C, Shaffery P, Yang R. Grid Edge Visibility: Gaps and a road map. *IEEE Electrif Mag* Dec. 2022;10(4):10–9. <https://doi.org/10.1109/MELE.2022.3211015>.
- [25] Angioni A, et al. Design and Implementation of a Substation Automation Unit. *IEEE Trans Power Delivery* 2017;32(2):1133–42. <https://doi.org/10.1109/TPWRD.2016.2614493>.
- [26] Palaniappan R, et al. Experimental verification of smart grid control functions on international grids using a real-time simulator. *IET Gener Transm Distrib* 2022;16(13):2747–60. <https://doi.org/10.1049/gtd.12486>.
- [27] Wilkinson M, Dumontier M, Aalbersberg I, et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data* 2016;3:160018. <https://doi.org/10.1038/sdata.2016.18>.
- [28] Hilal AR, Basir OA. A Scalable Sensor Management Architecture Using BDI Model for Pervasive Surveillance. *IEEE Syst J* 2015;9(2):529–41. <https://doi.org/10.1109/JSYST.2014.2334071>.
- [29] Song C, Havlin S, Makse HA. Self-similarity of complex networks. *Nature* 2005; 433:392–5. <https://doi.org/10.1038/nature03248>.
- [30] A. A. Amrane, N. Retière and D. M. Riu, "New Modeling of Electrical Power Networks Using Fractal Geometry," Proceedings of 14th International Conference on Harmonics and Quality of Power - ICHQP 2010, 2010, 10.1109/ICHQP.2010.5625440.
- [31] Le TTM, Retière N. Exploring the scale-invariant structure of smart grids. *IEEE Syst J* 2014;11(3):1612–21. <https://doi.org/10.1109/JSYST.2014.2359052>.
- [32] E. Ortjohann, P. Wirasanti, A. Schmelter, H. Saffour, M. Hoppe and D. Morton, "Cluster fractal model—A flexible network model for future power systems," International Conference on Clean Electrical Power (ICCEP), IEEE, 2013, pp. 293–297, 10.1109/ICCEP.2013.6587004.
- [33] S. Grobbelaar and M. Uliuru, "Complex networks as control paradigm for complex systems," IEEE International Conference on Systems, Man and Cybernetics, 2007, pp. 4069–4074, 10.1109/ICSMC.2007.4414262.
- [34] Ionita S. Multi Agent Holonic Based Architecture for Communication and Learning about Power Demand in Residential Areas. International Conference on Machine Learning and Applications 2009:644–9. <https://doi.org/10.1109/ICMLA.2009.87>.
- [35] Negeri E, Baken N, Popov M. Holonic Architecture of the Smart Grid. *Smart Grid and Renewable Energy* 2013;4:202–12. <https://doi.org/10.4236/sgre.2013.42025>.
- [36] Negeri E. Smart Power Grid: A Holonic Approach. PhD Technische Universiteit Delft 2014. <https://doi.org/10.4233/uuid:956cd759-ed0a-48c7-a311-0baa1d60f5df>.
- [37] H.F. Wedde, S. Lehnhoff, K. Moritz, C. Rehtanz and O. Krause, "Bottom-Up Self-Organization of Unpredictable Demand and Supply under Decentralized Power Management," 2nd IEEE International Conference on Self-Adaptive and Self-Organizing Systems, Venice, Italy, pp. 20–24, 2008, .
- [38] H.F. Wedde, S. Lehnhoff, C. Rehtanz and O. Krause, "Intelligent Agents under Collaborative Control in Emerging Power Systems," *Int. Journal of Engineering, Science and Technology (IJEST)*, Special Issue on Applications of CI in Emerging Power Systems, vol. 2, no. 3, pp. 45–59, 2010, 10.4314/ijest.v2i3.64994.
- [39] S. Ruthe, C. Rehtanz and S. Lehnhoff, "On the Problem of Controlling Shiftable Prosumer Devices with Price Signals," Proceedings of the 18th Power Systems Computation Conference (PSCC'14), Wrocław, Poland, 2014 and International Journal of Electrical Power and Energy System, Elsevier, Vol. 72, pp. 83–90, 2015, 10.1016/j.ijepes.2015.02.014.
- [40] Moyo C, Andrén FP, Strasser T, Heistracher T, Du J, Hofmann U. Towards a holonic-control inspired local market approach used in intelligent energy systems. In: *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*; 2016, p. 3930–5. <https://doi.org/10.1109/SMC.2016.7844848>.
- [41] Ansari J, Gholami A, Kazemi A. Multi-agent systems for reactive power control in smart grids. *Int J Electr Power Energy Syst* 2016;83. <https://doi.org/10.1016/j.ijepes.2016.04.010>.
- [42] Ounnar F, Naamane A, Pujo P, N. M'Sirdi "Intelligent Control of Renewable Holonic Energy Systems Energy Procedia," 2013;42:465–72. <https://doi.org/10.1016/j.egypro.2013.11.047>.
- [43] Diaconescu A, Menga D, Demeure IA, Frey S. "Holonic Control Architecture for a Heterogeneous Multi-Objective Smart Micro-Grid. In: "Proceedings of IEEE 7th International Conference on Self-Adaptive and Self-Organizing Systems(SASO); 2013, p. 21–30. <https://doi.org/10.1109/SASO.2013.11>.
- [44] Vlad V, Popa CD, Pentiu RD, Buzduga C. Control architecture for power distribution systems based on IEC 61850, IEC 61499 and holonic concepts. In: *International Conference and Exposition on Electrical and Power Engineering (EPE)*; 2014, p. 132–6. <https://doi.org/10.1109/ICEPE.2014.6969883>.
- [45] Florea G, Chenaru O, Dobrescu R, Popescu D. "A fractal model for Power Smart Grids," IEEE Conf. In: *Society, 20th International Conference on Control Systems and Science*; 2015. <https://doi.org/10.1109/CSCS.2015.104>.
- [46] Ferreira A, Leitão P. Holonic self-sustainable systems for electrical micro grids. In: *IEEE 14th International Conference on Industrial Informatics (INDIN)*; 2016, p. 510–5. <https://doi.org/10.1109/INDIN.2016.7819215>.
- [47] K. Piotrowski et al., "A hierarchical architecture for an energy management system," *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2016)*, 2016, 10.1049/cp.2016.1098.
- [48] Piotrowski K, et al. Balancing energy production and consumption in energy efficient neighborhoods. *IEEE International Energy Conference (ENERGYCON)* 2018. <https://doi.org/10.1109/ENERGYCON.2018.8398801>.
- [49] Howell S, Rezgui Y, Hippolyte J-L, Jayan B, Li H. Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources. *Renewable and Sustainable Energy Reviews*, Elsevier 2017;77: 193–214. <https://doi.org/10.1016/j.rser.2017.03.107>.
- [50] Ferreira A, Leitao P, Barata J. A Potential Field Load Scheduling Approach for Self-Sustainable Electrical Microgrids. In: *IEEE 28th International Symposium on Industrial Electronics (ISIE)*; 2019, p. 2585–90. <https://doi.org/10.1109/ISIE.2019.87813160>.
- [51] Nurdin Y, Muchallil S. Holonic Multi-Agent System for Microgrid Hierarchical Control. In: *IEEE International Conference on Cybernetics and Computational Intelligence (CyberneticsCom)*; 2019, p. 66–71. <https://doi.org/10.1109/CYBERNETICSCOM.2019.8875690>.
- [52] Abdel-Fattah MF, Kohler H, Rotenberger P, Schöler L. A Review of the Holonic Architecture for the Smart Grids and the Self-Healing Application. In: *21st International Scientific Conference on Electric Power Engineering (EPE)*; 2020. <https://doi.org/10.1109/EPES1172.2020.9269182>.
- [53] Choi JS. Energy Management Agent Frameworks: Scalable, Flexible, and Efficient Architectures for 5G Vertical Industries. *IEEE Ind Electron Mag* 2021;15(1): 62–73. <https://doi.org/10.1109/MIE.2020.3016917>.
- [54] Mayer J, et al. Holonic architectures for IoT-empowered energy management in districts. In: *IEEE 7th World Forum on Internet of Things (WF-IoT)*; 2021, p. 189–94. <https://doi.org/10.1109/WF-IoT51360.2021.9595252>.
- [55] Eger T, Grube T, Volk F, Mühlhäuser M. Holonic System Model for Resilient Energy Grid Operation. *MDPI Energies* 2021. <https://doi.org/10.3390/en14144120>.
- [56] Früh H, Müller S, Contreras D, Rudion K, von Haken A, Surmann B. Coordinated Vertical Provision of Flexibility From Distribution Systems. *IEEE Trans Power Syst* 2023;38(2):1834–44. <https://doi.org/10.1109/TPWRS.2022.3162041>.
- [57] Liu MZ, et al. Grid and Market Services From the Edge: Using Operating Envelopes to Unlock Network-Aware Bottom-Up Flexibility. *IEEE Power Energy Mag* 2021;19(4):52–62. <https://doi.org/10.1109/MPE.2021.3072819>.
- [58] S. Valipour, F. Volk, T. Grube, L. Böck, L. Karg and M. Mühlhäuser, "A Formal Holon Model for Operating Future Energy Grids during Blackouts," The 5th International Conference on Smart Cities and Green ICT Systems (Smartgreens), Rome, Italy, 2016, 10.5220/0005768801460153.
- [59] Albaker A, Khodaei A. Optimal Scheduling of Integrated Microgrids in Holonic Distribution Grids. *North American Power Symposium (NAPS)* 2018. <https://doi.org/10.1109/NAPS.2018.8600671>.
- [60] Liang N, He X, Tan J, Pan Z, Zheng F. Stackelberg game-based optimal scheduling for multi-community integrated energy systems considering energy interaction and carbon trading. *Int J Electr Power Energy Syst* 2023;153. <https://doi.org/10.1016/j.ijepes.2023.109360>.
- [61] Pahwa A, et al. Goal-Based Holonic Multiagent System for Operation of Power Distribution Systems. *IEEE Trans Smart Grid* 2015;6(5):2510–8. <https://doi.org/10.1109/TSG.2015.2404334>.
- [62] B. Uhlemeyer, J. Jakob, M. Zdrallek, "The cellular approach as a principle in integrated energy system planning and operation," *CIRE2020 Workshop*, Berlin, 2020, .
- [63] Flatter F, Mohammadi S, Wellssow W. Structure, Planning and Operation of a Cellular Energy System in 2050. *VDE ETG Congress 2021:18–9*. URL: 9469525.
- [64] Schinke-Nendza A, Blumberg G, Weber C. A Novel Design for Electricity Markets based on the Cellular Approach. In: *17th International Conference on the European Energy Market (EEM)*; 2020. <https://doi.org/10.1109/EEM49802.2020.9221982>.
- [65] D. Mayorga Gonzalez, C. Rehtanz and J. Myrzik, "The Smart Power Cell Concept: Mastering TSO-DSO Interactions for the Secure and Efficient Operation of Future Power Systems," *IET Generation, Transmission & Distribution*, vol. 14, no. 13, 2020, pp. 2407–2418, 10.1049/iet-gtd.2019.0991.
- [66] Vaccaro A, Popov M, Villacci D, Terzija V. An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification. *Proc IEEE* 2011;99:119–32. <https://doi.org/10.1109/JPROC.2010.2081651>.
- [67] Dörfler F, Simpson-Porco JW, Bullo F. Breaking the Hierarchy: Distributed Control and Economic Optimality in Microgrids. *IEEE Trans Control Network Syst* 2016;3(3):241–53. <https://doi.org/10.1109/T CNS.2015.2459391>.
- [68] Hug G, Kar S, Wu C. Consensus + Innovations Approach for Distributed Multiagent Coordination in a Microgrid. *IEEE Trans Smart Grid* 2015;6(4): 1893–903. <https://doi.org/10.1109/TSG.2015.2409053>.
- [69] Cao Y, Li Y, Liu X, Rehtanz C. *Cyber-Physical Energy and Power Systems – Modeling Analysis and Application*. Springer-Verlag; 2019. 10.1007/978-981-15-0062-6.
- [70] Rehtanz C. *Autonomous Systems and Intelligent Agents in Power System Control and Operation*. Springer-Verlag; 2003. 10.1007/978-3-662-05955-5.
- [71] U. Häger, C. Rehtanz and S. Lehnhoff, "Analysis of the Robustness of a Distributed Coordination for Power Flow Controllers," *17th Power Systems Computation Conference, PSCC, Stockholm, 2011*, pp. 22–26, URL: <https://www.researchgate.net>.

- net/publication/236623098_Analysis_of_the_Robustness_of_a_Distributed_Coordination_System_for_Power_Flow_Controllers.
- [72] O. Pohl, F. Rewald, S. Dalhues, P. Jörke, C. Rehtanz, C. Wietfeld, A. Kubis, R. K. Tamgue and D. Kirsten, "Advancements in Distributed Power Flow Control," Proceedings of the 53rd International Universities Power Engineering Conference (IUPEEC), 2018, Glasgow, Scotland, 2018, 10.1109/IUPEEC.2018.8542100.
- [73] Pohl O, Dalhues S, Rehtanz C. "DC-sensitivities for impedance controllers in an agent-based power flow control system," IEEE Power & Energy Society Innovative Smart Grid Technologies Conference Europe (ISGT), Sarajevo. Bosnia and Herzegovina 2018;pp. 21.-25. <https://doi.org/10.1109/ISGT.2018.8403390>.
- [74] Merat N, et al. The "Out-of-the-Loop" concept in automated driving: proposed definition, measures and implications. Cogn Tech Work 2019;21(1):87-98. <https://doi.org/10.1007/s10111-018-0525-8>.
- [75] VDE ETG Task Force: "Hochautomatisierung von Nieder- und Mittelspannungsnetzen," 2021-2022, URL: <https://www.vde.com/de/etg/arbeitsgebiete/v2/hochautomatisierung-von-nieder-und-mittelspannungsnetzen>.
- [76] VDE. ETG Task Force "Digitaler Zwilling / Digital Twin," 2021-2022, URL: <https://www.vde.com/de/etg/arbeitsgebiete/v2/hochautomatisierung-von-nieder-und-mittelspannungsnetzen>.
- [77] M. Ilić, "Transforming supervisory control and data acquisition (SCADA) into Dynamic Monitoring and Decision Systems (DYMONDS): The missing link in smart grids," IEEE PES General Meeting, 2010, pp. 1-4, .
- [78] Ilić MD. Dynamic Monitoring and Decision Systems for Enabling Sustainable Energy Services. Proc IEEE 2011;99(1):58-79. <https://doi.org/10.1109/JPROC.2010.2089478>.
- [79] M. Ilic, J. -Y. Joo, P. M. S. Carvalho, L. A. F. M. Ferreira and B. Almeida, "Dynamic monitoring and decision systems (DYMONDS) framework for reliable and efficient congestion management in smart distribution grids," 2013 IREP Symposium Bulk Power System Dynamics and Control - IX Optimization, Security and Control of the Emerging Power Grid, 2013, 10.1109/IREP.2013.6629401.
- [80] Ilic MD. Toward a unified modeling and control for sustainable and resilient electric energy systems. Foundations and Trends in Electric Energy Systems 2016; 1(1-2):1-141. <https://doi.org/10.1561/3100000002>.
- [81] Joo JY, Ilic MD. 2016, "An information exchange framework utilising smart buildings for efficient microgrid operation," Proc IEEE 2016;104(4):858-64. <https://doi.org/10.1109/JPROC.2016.2526119>.
- [82] Ilic M, Xie L, Liu Q. "Engineering IT-Enabled Electricity Services: The Case of Low-Cost Green Azores Islands - In: the Tale of Two Low-Cost Green Azores data," Springer Science+Business Media New York; 2013. <https://doi.org/10.1007/978-0-387-09736-7>.
- [83] Tulabing RS, Mitchell BC, Covic GA. Localized management of distributed flexible energy resources. Int J Electr Power Energy Syst 2024;157. <https://doi.org/10.1016/j.ijepes.2024.109790>.
- [84] Fan Z, et al. Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities. IEEE Commun Surv Tutorials 2013;15(1):21-38. <https://doi.org/10.1109/SURV.2011.122211.00021>.
- [85] C. Bektas, D. Overbeck and C. Wietfeld, "SAMUS: Slice-Aware Machine Learning-based Ultra-Reliable Scheduling," IEEE International Conference on Communications (ICC), Virtual Event, 2021, 10.1109/ICC42927.2021.9500837.
- [86] D. Overbeck, F. Kurtz, S. Böcker, C. Wietfeld, "Design of a 5G Network Slicing Architecture for Mixed-Critical Services in Cellular Energy Systems", In 2022 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Singapore, 2022.
- [87] IEEE International Conference on Communications (ICC), Virtual Event 2021. <https://doi.org/10.1109/ICC42927.2021.9500837>.
- [88] Monhof S, Böcker S, Tiemann J, Wietfeld C. "Cellular Network Coverage Analysis and Optimization in Challenging Smart Grid Environments", In 2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm). Denmark: Aalborg; October 2018.
- [89] Dorsch N, Kurtz F, Wietfeld C. Enabling Hard Service Guarantees in Software-Defined Smart Grid Infrastructures. In Computer Networks, Elsevier December 2018;147:112-31.
- [90] Wiebusch R, Wagner NA, Overbeck D, Kurtz F, Wietfeld C. "Towards Open 6G: Experimental O-RAN Framework for Predictive Uplink Slicing," In 2023 IEEE International Conference on Communications (ICC). Rome: Italy; 2023.
- [91] Mahmood NH, Böcker S, et al. Machine type communications: key drivers and enablers towards the 6G era. In EURASIP Journal on Wireless Communications and Networking 2021;2021(1):134.
- [92] Arendt C, Böcker S, Wietfeld C. Data-Driven Model-Predictive Communication for Resource-Efficient IoT Networks. In 2020 IEEE 6th World Forum on Internet of Things (WF-IoT). 2020.
- [93] Kleinschmidt T, Wietfeld C. "Fluctuation-Sensitive Model-Predictive Communication for Distributed Energy Resources", In IEEE ICC 2016 Workshop on Integrating Communications, Control, and Computing Technologies for Smart Grid. Malaysia: Kuala Lumpur; 2016.
- [94] Strinati E, Barbarossa S. 6G networks Beyond Shannon towards semantic and goal-oriented communications. Comput Netw 2021;190. <https://doi.org/10.1016/j.comnet.2021.107930>.
- [95] Uysal E, et al. Semantic Communications in Networked Systems: A Data Significance Perspective. IEEE Netw 2022;36(4):233-40. <https://doi.org/10.1109/MNET.106.2100636>.
- [96] Erol-Kantarci M, Moutfah HT. Energy-efficient information and communication infrastructures in the smart grid: a survey on interactions and open issues. IEEE Commun Surv 2015;17(1):179-97. <https://doi.org/10.1109/COMST.2014.2341600>.
- [97] Zhang S, et al. Practical Adoption of Cloud Computing in Power Systems—Drivers, Challenges, Guidance, and Real-World Use Cases. IEEE Trans Smart Grid 2022;13(3):2390-411. <https://doi.org/10.1109/TSG.2022.3148978>.
- [98] Samie F, et al. "Edge Computing for Smart Grid: An Overview on Architectures and Solutions," IoT for Smart Grids. Power Systems. Cham: Springer; 2019. 10.1007/978-3-030-03640-9_2.
- [99] F. Samie, L. Bauer and J. Henkel. "IoT technologies for embedded computing: a survey" CODES+ISSS, ACM., 2016, pp. 8:1-8:10, ISBN: 978-1-4503-4483-8 10.1145/2968456.2974004.
- [100] Maasoumy M, Sangiovanni-Vincentelli A. Smart connected buildings design automation: Foundations and trends. Foundations and Trends in Electronic Design Automation 2016;10(1-2):1-143. <https://doi.org/10.1561/10000000043>.
- [101] Duan T, Huang Z, Dinavahi V. RTCE: Real-Time Co-Emulation Framework for EMT-Based Power System and Communication Network on FPGA-MPSoc Hardware Architecture. IEEE Trans Smart Grid 2021;12(3):2544-53. <https://doi.org/10.1109/TSG.2020.3039259>.
- [102] D. Pathak, H. Homayoun and I. Savidis, "Smart grid on chip: Work load-balanced on-chip power delivery," IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 25, no.9, 2017, pp. 2538-2551. 10.1109/TVLSI.2017.2699644.
- [103] Hamann A, Saidi S, Ginthoer D, Wietfeld C, Ziegenbein D. Building End-to-End IoT Applications with QoS Guarantees. In: 57th ACM/IEEE Design Automation Conference (DAC); 2020. p. 1-6. <https://doi.org/10.1109/DAC18072.2020.9218564>.
- [104] N. Dutt, A. Jantsch, and S. Sarma, "Toward Smart Embedded Systems: A Self-aware System-on-Chip (SoC) Perspective," ACM Trans. Embed. Comput. Syst, Vol.15, no. 2, 2016, 10.1145/2872936.
- [105] Rambo EA, et al. The Self-Aware Information Processing Factory Paradigm for Mixed-Critical Multiprocessing. IEEE Trans Emerg Top Comput 2022;10(1): 250-66. <https://doi.org/10.1109/TETC.2020.3011663>.
- [106] Saidi S, Ziegenbein D, Deshmukh JV, Ernst R. Autonomous Systems Design: Charting a New Discipline. IEEE Des Test 2022;39(1):8-23. <https://doi.org/10.1109/MDAT.2021.3128434>.
- [107] EU Commission (2020). A European Strategy for Data, URL: https://ec.europa.eu/info/sites/info/files/communication-european-strategy-data-19feb2020_en.pdf.
- [108] EU Commission (2021a). Data Act & amended rules on the legal protection of databases. Brussels, URL: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13045-Data-Act-&-amended-rules-on-the-legal-protection-of-databases_en.
- [109] EU Commission (2021b). The Digital Services Act package: The Digital Services Act and Digital Markets Act encompass a single set of new rules applicable across the whole EU to create a safer and more open digital space, URL: <https://digital-strategy.ec.europa.eu/en/policies/digital-services-act-package>.
- [110] EU Commission (2021c). Regulatory framework proposal on artificial intelligence: The Commission is proposing the first-ever legal framework on AI, which addresses the risks of AI and positions Europe to play a leading role globally, URL: <https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai>.
- [111] C.Hedeler, K. Belhajjame, N. W. Paton, A. Campi, A. A. Fernandes and S. M. Embury, "Dataspaces," In Search Computing," 2010, Chapter 7: Dataspaces, vol 5950, Springer, Berlin, Heidelberg, pp. 114-134, 10.1007/978-3-642-12310-8_7.
- [112] F. Aulkemeier, M.-E. Jacob and J. van Hillegersberg, "Platform-based collaboration in digital ecosystems. Electronic Markets," vol.29, no.4, 2019, pp. 597-608, 10.1007/s12525-019-00341-2.
- [113] M.I.S. Oliveira and B. F. Lóscio, "What is a Data Ecosystem? In M. Janssen, S. A. Chun, V. Weerakkody (Eds.)," Proceedings of the 19th Annual International Conference on Digital Government Research Governance in the Data Age - dgo '18, 2018, pp. 1-9, 10.1145/3209281.3209335.
- [114] Capiello C, Gal A, Jarke M, Rehof J. "Data Ecosystems," Sovereign Data Exchange among Organizations (Dagstuhl Seminar 19391). Advance online publication 2020. <https://doi.org/10.4230/DagRep.9.9.66>.
- [115] T.M. Guggenberger, F. Möller, T. Haarhaus, I. Gür, B. Otto, "Ecosystem Types in Information Systems," ECIS., 2020, URL: https://www.researchgate.net/publication/341188637_ECOSYSTEM_TYPES_IN_INFORMATION_SYSTEMS.
- [116] Curry E. "Real-time Linked Dataspaces: Enabling Data Ecosystems for Intelligent Systems," Springer. Nature 2020. <https://doi.org/10.1007/978-3-030-29665-0>.
- [117] Franklin M, Halevy A, Maier D. databases to dataspaces. ACM SIGMOD Rec 2005; 34(4):27-33. <https://doi.org/10.1145/1107499.1107502>.
- [118] Halevy A, Franklin M, Maier D. Principles of dataspaces systems. In: Proceedings of the twenty-fifth ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems; 2016. <https://doi.org/10.1145/1142351.1142352>.
- [119] Pellegrini T. Semantic metadata in the publishing industry - technological achievements and economic implications. Electron Mark 2017;27(1):9-20. <https://doi.org/10.1007/s12525-016-0238-x>.
- [120] S. Dalmolen, H.J. Bastiaansen, M. Kollenstart, M. Punter, "Infrastructural sovereignty over agreement and transaction data (" metadata") in an open network-model for multilateral sharing of sensitive data," 40th International Conference on Information Systems 2020, URL: <https://research.utwente.nl/en/publications/infrastructural-sovereignty-over-agreement-and-transaction-data-m>.
- [121] Innopac, "Data sovereignty and soft infrastructure: key enablers of the European data economy," 2020, URL: en/media/728/download.
- [122] Nagel L, Lycklama D. "Design Principles for Data Spaces" Position Paper. Zenodo Retrieved 2021. <https://doi.org/10.5281/zenodo.5105744>.
- [123] O.Hanseth and E. Monteiro, "Understanding information infrastructure," Unpublished Manuscript, URL: <https://www.researchgate.net/profile/Eric>

- Monteiro-2/publication/265066841_Understanding_Information_Infrastructure/links/546dee010cf2d5ae36708bd0/Understanding-Information-Infrastructure.pdf.
- [124] Tilson D, Lyytinen K, Sørensen C. Research Commentary —Digital Infrastructures: The Missing IS Research Agenda. *Inf Syst Res* 2010;21(4):748–59. <https://doi.org/10.1287/isre.1100.0318>.
- [125] A. Castro, J. Machado, M. Roggendorf and H. Soll, "How to build a data architecture to drive innovation—today and tomorrow," URL: <https://www.mckinsey.de/business-functions/mckinsey-digital/our-insights/how-to-build-a-data-architecture-to-drive-innovation-today-and-tomorrow>.
- [126] Kramberg P, Heinzl A. Datenplattformökosysteme. *HMD Praxis Der Wirtschaftsinformatik* 2021;58(3):477–93. <https://doi.org/10.1365/s40702-021-00716-0>.
- [127] Hein A, Schrieck M, Riasanow T, Setzke DS, Wiesche M, Böhm M, et al. Digital platform ecosystems. *Electron Mark* 2020;30(1):87–98. <https://doi.org/10.1007/s12525-019-00377-4>.
- [128] B. Pourebrahimi, K. Bertels and S. Vassiliadis, "A survey of peer-to-peer networks," Proceedings of the 16th annual workshop on Circuits, Systems and Signal Processing, 2005, pp. 570–577, 10.1145/1041680.1041681.
- [129] Sheth AP, Larson JA. Federated database systems for managing distributed, heterogeneous, and autonomous databases. *ACM Computing Surveys (CSUR)* 1990;22(3):183–236. <https://doi.org/10.1145/96602.96604>.
- [130] S. Busse, R. D. Kutsche and U. Leser, "Strategies for the Conceptual Design of Federated Information Systems," EFIS. Symposium conducted at the meeting of Citeseer, 2020, <https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.31.7959>.
- [131] Heimbigner D, McLeod D. A federated architecture for information management. *ACM Transactions on Information Systems (TOIS)* 1985;3(3):253–78. <https://doi.org/10.1145/4229.4233>.
- [132] E. Sun, K. Meng, R. Yang, Y. Zhang and M. Li, "Research on Distributed Data Sharing System based on Internet of Things and Blockchain," *Journal of Systems Science and Information*, vol.9, no.3, 2021, pp. 239–254, 10.21078/JSSI-2021-239-16.
- [133] M. Swan, "Blockchain: Blueprint for a new economy," O'Reilly Media, URL: 10.5555/3006358.
- [134] M. Van Steen and A.S. Tanenbaum, "A brief introduction to distributed systems," *Computing*, vol 98, no.10, pp. 967–1009, 10.1007/s00607-016-0508-7.
- [135] Mühle A, Grüner A, Gayvoronskaya T, Meinel C. A survey on essential components of a self-sovereign identity. *Computer Science Review* 2018;30:80–6. <https://doi.org/10.1016/j.cosrev.2018.10.002>.
- [136] Yohanandhan RV, Elavarasan RM, Pugazhendhi R, Premkumar M, Mihet-Popa L, Terzija V. A holistic review on Cyber-Physical Power System (CPPS) testbeds for secure and sustainable electric power grid – Part – I: Background on CPPS and necessity of CPPS testbeds. *Int J Electr Power Energy Syst* 2022;136. <https://doi.org/10.1016/j.ijepes.2021.107718>.
- [137] Yohanandhan RV, Elavarasan RM, Pugazhendhi R, Premkumar M, Mihet-Popa L, Terzija V. A holistic review on Cyber-Physical Power System (CPPS) testbeds for secure and sustainable electric power grid – Part – II: Classification, overview and assessment of CPPS testbeds. *Int J Electr Power Energy Syst* 2022;137. <https://doi.org/10.1016/j.ijepes.2021.107721>.
- [138] Kermani AY, Abdollahi A, Rashidinejad M. Cyber-secure energy and flexibility scheduling of interconnected local energy networks with introducing an XGBoost-assisted false data detection and correction method. *Int J Electr Power Energy Syst* 2024;155. <https://doi.org/10.1016/j.ijepes.2023.109683>.
- [139] Communication networks and systems for power utility automation – Part 6: Configuration description language for communication in electrical substations related to IEDs, IEC 61850-6:2010, International Electrotechnical Commission, 2010.
- [140] D. Hilbrich, "Universelles Prüfsystem für innovative Schutz- und Automatisierungssysteme in Smart Grids," Shaker Verlag, Band 22, 2021, ISBN 9783844083088.
- [141] Palaniappan R, et al. Experimental Verification of Smart Grid Functions on Real-World Grids using a Real-time simulator. *IET Gener Transm Distrib* 2022;16(13):2747–60. <https://doi.org/10.1049/gtd2.12486>.
- [142] Palaniappan R, Molodchik O, Rehtanz C. Hardware Implementation of an OPF Algorithm in a Distribution Network with Decentralised Measurements. *CIRE Open Access Journal* 2020;1:580–3. <https://doi.org/10.1049/oap-cired.2021.0122>.
- [143] S. Racza et al., "A novel Software Applications Rollout and Monitoring Strategy for Enabling the Transition to Electromobility in future Smart Grids," CIRE Porto Workshop, 2022.
- [144] Energy management system application program interface (EMS-API) - Part 301: Common information model (CIM) base, IEC 61970-301:2020, International Electrotechnical Commission, 2020.
- [145] Brosinsky C. On power system automation: A Digital Twin-centric framework for the next generation of energy management systems, 10.22032/dbt.54812. Technical University of Ilmenau; 2023. PhD Dissertation.
- [146] T. Schwierz, "Application of Digital Twin in Electrical Distribution Grids," TU Dortmund University, Germany.
- [147] Silva J, Sumaili J, Bessa RJ, Seca L, Matos MA, Miranda V, et al. Estimating the Active and Reactive Power Flexibility Area at the TSO-DSO Interface. *IEEE Trans Power Syst* 2018;33(5):4741–50. <https://doi.org/10.1109/TPWRS.2018.2805765>.
- [148] Contreras DA, Rudion K. Time-Based Aggregation of Flexibility at the TSO-DSO Interconnection Point. *IEEE* 2019. <https://doi.org/10.1109/PESGM40551.2019.8973421>.
- [149] Chapman N, Zhang L, Good N, Mancarella P. Exploring flexibility of aggregated residential electric heat pumps. 2016 IEEE International Energy Conference (ENERGYCON), IEEE 2016. <https://doi.org/10.1109/ENERGYCON.2016.7514082>.
- [150] A. Ulbig, G. Andersson, "Analyzing operational flexibility of electric power systems," *International Journal of Electrical Power & Energy Systems*, vol. 72, pages 155–164, Elsevier, 2015, 10.1016/j.ijepes.2015.02.028.
- [151] S. Kundu, K. Kalsi, S. Backhaus, "Approximating Flexibility in Distributed Energy Resources: A Geometric Approach," 2018. 10.23919/PSCC.2018.8442600.
- [152] Contreras DA, Rudion K. Improved Assessment of the Flexibility Range of Distribution Grids Using Linear Optimization. *IEEE* 2018. <https://doi.org/10.23919/PSCC.2018.8442858>.
- [153] D. Mayorga Gonzalez, J. Hachenberger, J. Hinker, F. Rewald, U. Hager, C. Rehtanz, J. Myrzik, "Determination of the Time-Dependent Flexibility of Active Distribution Networks to Control Their TSO-DSO Interconnection Power Flow," 2018. 10.23919/PSCC.2018.8442865.
- [154] D. Contreras, "Estimation of flexibility potentials in active distribution networks," PhD thesis, Norderstedt (2021).
- [155] Contreras DA, Rudion K. Computing the feasible operating region of active distribution networks: Comparison and validation of random sampling and optimal power flow-based methods. *IET Gener Transm Distrib* 2021;15(10):1600–12. <https://doi.org/10.1049/gtd2.12120>.
- [156] Usman M, Alizadeh MI, Capitanescu F, Avramidis I-I, Madureira AG. A novel two-stage TSO–DSO coordination approach for managing congestion and voltajes. *Int J Electr Power Energy Syst* 2023;147. <https://doi.org/10.1016/j.ijepes.2022.108887>.
- [157] T. Offergeld, "Intertemporal Characterisation of Aggregated Flexibility Potentials in Electric Power Systems," PhD thesis, RWTH Aachen, 2024.
- [158] T. Offergeld, N. Mattus, F. Schmidtke, A. Ulbig, "On Aggregation Performance in Privacy Conscious Hierarchical Flexibility Coordination Schemes," 11th Bulk Power Systems Dynamics and Control Symposium (IREP 2022), 2022, 10.48550/arXiv.2207.03439.
- [159] T. Offergeld, F. Klein-Helmkamp, A. Selimaj, A. Ulbig, "Analysis of the Feasibility Region of Hierarchical Flexibility Coordination Schemes," 13th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, Medpower, 2022. URL: .