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Architectural and functional classification of smart grid solutions

Friederike Wenderoth[1,2*], Elisabeth Drayer[2,3], Robert Schmoll[4], Michael Niedermeier[5] and Martin Braun[1,2]

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*Correspondence:
friederike.wenderoth@iee.fraunhofer.de
[1]Department Grid Planning and Grid Operation, Fraunhofer IEE, Kassel, Germany
[2]Department of Energy Management and Power System Operation, University of Kassel, Kassel, Germany
Full list of author information is available at the end of the article

Abstract
Historically, the power distribution grid was a passive system with limited control capabilities. Due to its increasing digitalization, this paradigm has shifted: the passive architecture of the power system itself, which includes cables, lines, and transformers, is extended by a communication infrastructure to become an active distribution grid. This transformation to an active system results from control capabilities that combine the communication and the physical components of the grid. It aims at optimizing, securing, enhancing, or facilitating the power system operation. The combination of power system, communication, and control capabilities is also referred to as a "smart grid". A multitude of different architectures exist to realize such integrated systems. They are often labeled with descriptive terms such as "distributed," "decentralized," "local," or "central." However, the actual meaning of these terms varies considerably within the research community.
This paper illustrates the conflicting uses of prominent classification terms for the description of smart grid architectures. One source of this inconsistency is that the development of such interconnected systems is not only in the hands of classic power engineering but requires input from neighboring research disciplines such as control theory and automation, information and telecommunication technology, and electronics. This impedes a clear classification of smart grid solutions. Furthermore, this paper proposes a set of well-defined operation architectures specialized for use in power systems. Based on these architectures, this paper defines clear classifiers for the assessment of smart grid solutions. This allows the structural classification and comparison between different smart grid solutions and promotes a mutual understanding between the research disciplines. This paper presents revised parts of Chapters 4.2 and 5.2 of the dissertation of Drayer (Resilient Operation of Distribution Grids with Distributed-Hierarchical Architecture. Energy Management and Power System Operation, vol. 6, 2018).

Keywords: Smart grid, Architecture, Communication network, Distributed control, Decentralized control, Central control

Introduction and motivation

In the last decade, research and industry have proposed many ways to realize solutions for the "smart grid." This is due to the rising requirement to integrate more distributed energy resources (DER) into the grid as well as increasing possibilities in information and communications technology (ICT). A smart grid solution includes functions for different tasks (e.g., voltage control, contingency management, self-healing, and islanding detection) under different conditions and time frames with various degrees of communication capabilities. In particular, the last aspect fundamentally changes the skills required to design such systems. In highly integrated solutions, ICT becomes as important as classic power engineering.

To distinguish the different operation methods, they are labeled with terms such as "decentralized," "distributed," "local," "central," "peer-to-peer," "agent-based," etc. These terms aim to classify these methods, but the definitions are sometimes vague. Chapter 5.1 of Drayer's dissertation (Drayer 2018) gives a list of examples from recent literature, that illustrate the confusion regarding the use of these terms. According to Drayer, clear definitions are missing in the current discussion (Drayer 2018). Due to the interdisciplinary nature of power system engineering, labelling terms are usually chosen according to the personal scientific background. Furthermore, if these terms are the basis for comparative analysis, the work becomes highly inaccurate.

The classic way to compare the performance of two smart grid solutions is to model them analytically and to numerically simulate and compare their behavior. This approach does not require any information about the structure and the type of method. However, this approach runs the risk of reducing a complex system to an oversimplified mathematical description. This might lead to important losses of characteristics. In a mere performance-based approach, solutions might be equal in their numeric model but require different infrastructures and conditions that would not be discovered (Drayer 2018).

For the assessment of a power system operation method, it is important to consider both: the performance of the method as well as its structure. This is particularly important for complex investigations such as those regarding reliability as in Syrri and Mancarella (2016), resilience and system security as mentioned in the relevant literature ((Biringer et al. 2013; Drayer 2018; Drayer et al. 2016)), and detailed in recent techno-economic analyses as in Stetz (2014); Stetz et al. (2014).

The aim of this paper is to define a set of classifiers that allow the assessment of the structure of grid operation methods. As illustrated by the examples in Chapter 5.1 of Drayer (2018), the key aspect is the explicit definition of architectural classifiers. For that purpose, this paper provides a review of major definitions for architectures used in related research disciplines in "System architectures in neighboring disciplines" section. These architectures are the background for the assessment classifiers introduced in "Assessment classifier" section. They allow the structural analysis and assessment of power system operation methods. In "Application" section a comprehensive classification of four power system operation methods is performed as an example.

System architectures in neighboring disciplines

Smart grid solutions comprise controllers, functionalities, and concepts for software and hardware, that can often be described by mathematical models that originate from research disciplines like control theory or automation. Yet, when it comes to the realization and implementation of such methods, this is often accomplished from an information or communication technology perspective. In this collaborative context, it is important to understand the basic terms of the other disciplines. This section introduces architectures of systems as they are designed in control theory in "Control theory" section, software development in "Software architecture" section, and communication in "Communication architectures" section. The architectural classifiers for power system operations proposed in "Operation architecture" section rely on these definitions. This section is a summary of Chapter 4.2 of Drayer's dissertation (Drayer 2018).

Control theory

The classification of control system architectures is stringent. The International Electrotechnical Commission (IEC) offers a database of international standard specifications of control systems.

A **Central** control systems is controlled by one controller. This controller has complete information about the system and sets all control variables related to the system (Lunze 1992). The standard IEC 60050-351-55-09 defines it as a "control structure with interconnected subprocesses, in which each partial control equipment considers the information of all subprocesses to form its output information" (International Electrotechnical Commission IEC).

Hierarchical control systems are distinguished between multilevel systems and multilayer systems. In a multilevel system, independent controllers cooperate to achieve the same goal (Lunze 1992). Higher-level units coordinate the lower levels. Conversely, in a multilayer system, each controller has its own objective, and the function to be realized by the control system is divided (Lunze 1992). According to IEC 60050-351-55-11, hierarchical control is a "control structure with several control levels placed one over the other, in which the control equipment assigned to a higher level coordinates the work of the control equipment assigned to the next lower level, providing, for instance, predetermining control tasks, command variables, reference variables, or final controlled variables" (International Electrotechnical Commission IEC).

In a **Decentralized** control architecture independent controllers control distinct subsystems. Importantly, no information is exchanged between them. In IEC 60050-351-55-10 decentralized control is defined as a "control structure with interconnected subprocesses in which each partial control equipment considers only the information from its associated subprocess to form its output information"(International Electrotechnical Commission IEC).

If there is an information exchange between the independent controllers, a control architecture is considered to be **Distributed**. It can be fully or partially distributed, depending on whether information is shared among all controllers or only with a subset of controllers.

Software architecture

The field of software architecture studies the structure of software systems and has its own terms for the classification of architecture types. Types of software architectures are e.g., the Client-Server architecture, where a clear separation between the provider of resources (server) and the user of resources (client) is realized. Another example is a Peer-to-peer architecture where every peer can communicate and use the resources of the other peers. In Khare (2002), the main characteristic of a decentralized software architecture is, that no central entity possesses "power" over the other entities. Contrarily, centralized software architectures always have a central entity and distributed architectures can exist with or without a central entity. Often systems are described as decentralized even if they actually have a central entity involved, but still distribute major parts of the processing tasks to lower level entities. A power system operation can often be seen as a distributed IT system.

Communication architectures

The Open Systems Interconnection model (OSI model) in ISO/IEC 7498-1 (International Organization for Standardization/International Electrotechnical Commission 1994) provides a detailed classification scheme of communication. It separates every (tele-) communication into seven layers, ranging from the physical transmission medium to the layer that directly interacts with the application that uses the communication. In the context of the Internet, this seven-layer model is reduced to a five-layer Internet protocol stack (Kurose and Ross 2013). In Baran (1964) a high-level classification of communication network architectures can be found, where the communication networks are differentiated between decentralized, distributed and centralized.

Assessment classifier

This section is a revised and extended version of the Chapter 5.2. from Drayer's dissertation (Drayer 2018).

As mentioned in the introduction, solutions for smart grid applications, or more generally power system operation methods, are usually extensive structures. They combine functions on different geographic levels and time scales with varying objectives and communication requirements. For the assessment of power system operation methods, a clear classification is needed. In Braun and Strauss (2008) a classification of commercial aggregation approaches of DER is proposed, which already respects the communication between actors in the grid, but does not consider actual control architectures or specific objectives. The European Committee for Standardization (CEN) also realized this quite early and published 2012 the “Smart Grid Reference Architecture” (SGAM)(CEN-CENELEC-ETSI 2012). It is a framework that allows for the classification and description of a specific method or use case for the smart grid. It differentiates five layers: business, function, information, communication and component. However, the SGAM does not comprise the necessary vocabulary for the classification of the operation architecture. For the evaluation of power system operation methods, more detailed classification schemes, such as the OSI model for the classification of the communication are necessary. The classifiers in this paper are contextualized using the SGAM. They are meant to complement the SGAM from the power system operation perspective.

The classifiers adapted from (Drayer 2018) are: **Objective(s)**, **Operation Architecture**, and **Communication**. They are described in more detail in the following sections.

Objective(s)

The **Objective** is the purpose of the power system operation method. E.g., voltage stability support or the provision of ancillary services. Sometimes they are multi-objective and even contradict each other e.g. the minimization of grid losses and the maximization of power feed in from renewable energies. The objective of a solution must always be seen in context with its operational constraints, such as the maximal capacity of lines or minimum voltage level. Constraints can even be caused by regulation. A list of possible objectives of power system operation methods can be found in Arnold et al. (2011). An objective can originate in all zones, domains and layers of the SGAM (CEN-CENELEC-ETSI 2012). The objective of an approach should be measurable to enable the quantification and assessment of the performance of a power system operation method.

Operation architecture

The classifier **Operation Architecture** is subdivided into the input data, the method, and the output or control variables. Operation architecture in this work refers not only to the mathematical or conceptual model of the "control architecture" but includes the requirements on communication capabilities as well. The operation architecture has a direct effect on the system security and resilience (Drayer 2018) and therefore is an important classifier for smart grid solutions. It comprises the SGAM zones operation, station, field and process in the function, information and component layer of the SGAM (CEN-CENELEC-ETSI 2012). In Nieße (2015) a classification of coordination paradigms is provided based on the location in which data is processed and where control decisions are made. This was developed for the classification of agent-based systems, but can be applied to classify the realization of power system operation methods in general. In the following, when discussing an operation unit, we mean the entity, in which information is processed and decisions for the operation are made.

Local operation architecture

The local architecture limits the control on one device or one facility. The input data must be available locally, and no external external communication is present. The operation unit of the PV system and the operation unit of the transformer tap control in Fig. 1 are examples of a local architecture. The operation unit is located at the controlled element, from which it receives measurements directly. It directly sends back set points to the physical actors of the respective facility or device.

Decentralized operation architecture

Figure 2 shows an example for a decentralized architecture, where one operation unit is assigned to several facilities or devices. Communication is established between the operation unit and the devices, but not between operation units. In Groumpos (1993),

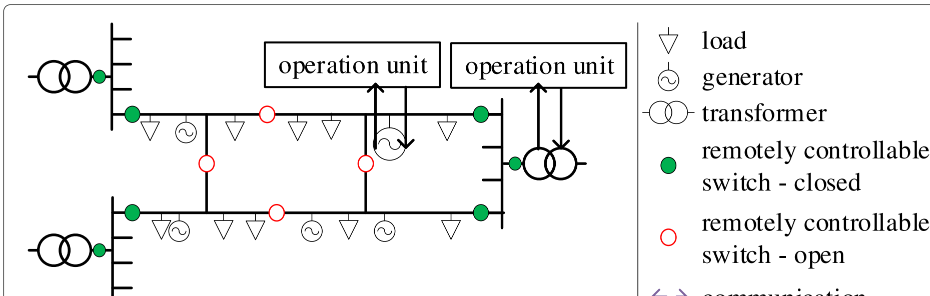

Fig. 1 Local operation architecture for a PV system and transformer. Source: Adapted from Drayer (2018)

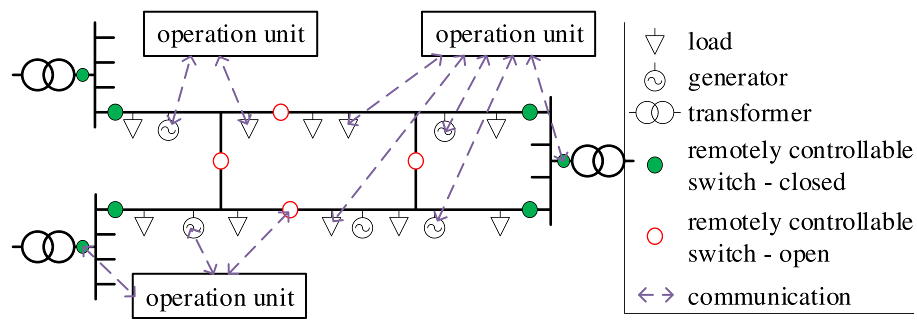

Fig. 2 Decentralized operation architecture for the operation of a distribution grid. Each of the three decentralized operation units operates the grid area of a primary substation. Source: Adapted from Drayer (2018)

a multilevel hierarchical system as in "Control theory" section is described, but in contradiction to the definition here, the according controller is considered a "partially decentralized" controller. In Zuniga (2017) the definition of a "decentralized" architecture comprises a hierarchical structure with a coordinating supervisory entity as well. This contradicts the definition of IEC (International Electrotechnical Commission IEC). According to Srikantha and Kundur (2019) in a decentralized architecture, no central unit is involved into actuating or coordination, but units throughout the system are still able to exchange information. However, in a decentralized operation architecture, solutions are calculated, and decisions made directly inside the decentral units, without coordination among operation units. A classification based on where decisions are taken has been suggested in Nieße (2015) as well. According to IEC (International Electrotechnical Commission IEC), we recommend the use of the word decentralized for systems without a central coordinating or supervising unit. As decentralized architectures do not have a single point of failure by design, they are often considered to be more resilient (Srikantha and Kundur 2019; Drayer 2018).

Distributed operation architecture

In a distributed architecture, one operation unit is assigned to one or more devices as well. Additionally, operation units are able to communicate and coordinate among each other. In Fig. 3, a fully connected distributed architecture is illustrated. Distributed operation architectures can be organized in a hierarchical or heterarchical fashion (Kamphuis et al.

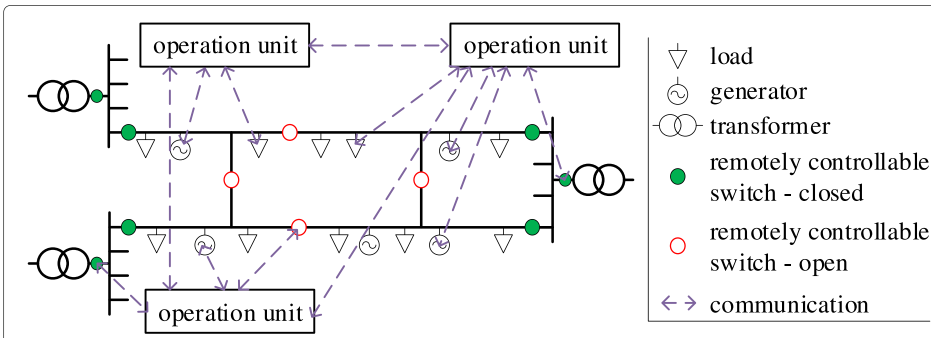

Fig. 3 Distributed operation architecture for the operation of a distribution grid. The three distributed operation units can exchange information with each other. Source: Adapted from Drayer (2018)

2015). Another term used for hierarchical operation architectures is "coordinated" (van Schuppen 2015; Oerter and Neusel-Lange 2014).

Hierarchical operation architecture

In a hierarchical architecture, the operation units are organized in several levels with a clear hierarchy and mutual dependency. Often, higher levels take over the more coordinating tasks. The higher level is the supervisory level for the lower level as can be seen in Fig. 4, where the higher level control center coordinates the operation units of the primary substations.

Hierarchical operation architectures are often distributed, but they can be a combination of a central and local architecture as well, where the SCADA is able to reduce the active power injection of a PV plant, and the local control of the PV plant controls the reactive power based on a local voltage measurement. Such a hierarchical concept is in line with (International Energy Agency 2002) as presented in Nieße et al. (2014) where distributed control in energy systems is defined as a hierarchical concept with coordination between separate systems.

Central operation architecture

When a single central operation unit controls all other devices in a system and aggregates and processes all the relevant information, a central operation architecture is present. Figure 5 shows an example, in which the control center is the single operation unit that operates the complete system. The supervisory control and data acquisition (SCADA) of a network operator can be seen as a central operation and contains the monitoring of the grid state and remote control of several elements in the network, such as remote switches.

Architecture overview

The following Table 1 gives an overview of the different architectures. The classification into the categories can easily be done by examining the number of operation units and controlled elements and determining whether the operation units communicate with each other. Hierarchical or heterarchical architectures can be combinations of the architectures in this table.

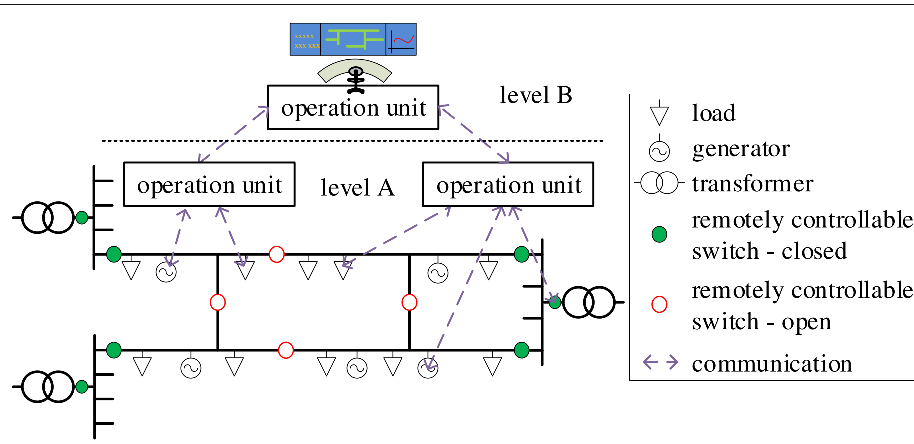

Fig. 4 Hierarchical operation architecture for a distribution grid with two layers: lower level A and supervisory level B. Source: Adapted from Drayer (2018)

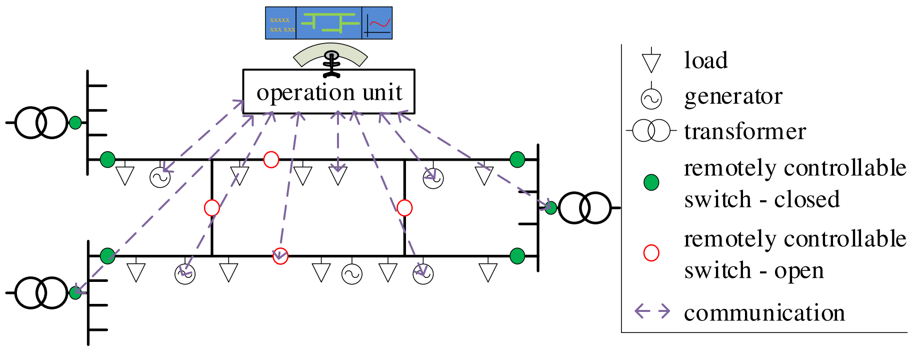

Fig. 5 Central operation architecture for a distribution grid operation based in the control center of the network operator. Source: Adapted from Drayer (2018)

It must be stated conclusively that the type of architecture also depends on the perspective of the description. For a small grid area that is controlled from an operation unit in the substation, the grid operation for this single grid area may be a central architecture in itself, but it may also be considered a decentralized operation architecture if the same principle is described for a larger grid area with several substations, each controlling its own underlying grid area.

Input and control variables

For the classification of a smart grid solution, it is also important to note the **Input and Control Variables**, because the same objective can be addressed using different physical input control variables. In addition, the same control variables can be used to reach different objectives. This classifier describes the physical parameters that are used as the basis for the models. Input variables can be divided into measurements and set point values. The control variables can be set point values that are forwarded to other operation units for further calculations or can be actual physical quantities. In the SGAM this corresponds to the information layer (CEN-CENELEC-ETSI 2012). In Drayer (2018) a non-exhaustive collection of possible input and control variables in the context of power systems is provided, such as voltage, active and reactive power or weather forecast data. The choice of the input and control variables defines the need for sensors and actors and therefore is an economic classifier as well.

Method

The **Method** describes the approach or algorithm that is used inside the operation unit(s) to realize the objective of the operation method. Like the objective, it is anchored in the function layer of the SGAM (CEN-CENELEC-ETSI 2012). A wide variety of methods are available and were explored in recent research works as explained in Chapter 5.2.2 of Drayer (2018). The method implies the costs for remote terminal units (RTUs), control center hardware, and software (e.g., an optimization-based approach requires more

Table 1 Analysis of smart grid solutions according to the Assessment Classifiers

	Local	Decentralized	Distributed	Central
Number of operation units	1	> 1	> 1	1
Number of controlled elements	1	> 1	> 1	> 1
Coordination between operation units	No	No	Yes	No

computation resources than a simple two-point controller). This again determines the set of connected sensors and actuators.

Communication

A fundamental characteristic of a smart grid is the communication capability of the devices in the grid. The combination of the power system and a communication system builds an interconnected network. In order to characterize a power system operation method, a clear definition of the required communication capabilites is indispenable, which is the aim of this classifier. Communication is often the bottleneck of new power system operation methods, as it is limited in reliability, latency, bandwidth, and security (Drayer 2018). The design of the communication parameters often is a trade-off between these parameters. Currently, much work has been conducted on optimizing protocol parameters, but in general the enhancement of these parameters results in increasing costs and maintenance. The classifier communication comprises parts of the communication, component, and information layers from the SGAM (CEN-CENELEC-ETSI 2012).

The conceptual Open Systems Interconnection model (OSI model) (International Organization for Standardization/International Electrotechnical Commission 1994) was developed for the classification of communication functions of telecommunication or computing systems. It can be adapted to communication in the power system context but is too detailed for the approach chosen in this paper. The five-layer model developed in Kurose and Ross (2013) is adapted for the classification proposed in this work. The three main classifiers for power system communication presented in the following sections are information flow, service layer, and technological realization.

Information flow

The **Information Flow** can be interpreted as the input and control data, according to "Input and control variables" section, that need to be communicated between the actors. It includes timely requirements and process-related constraints. According to Kurose and Ross (2013), this is equivalent to the application layer (e.g., for a centralized operation architecture, the information flow usually is unidirectional from the control center to the generators). In the SGAM (CEN-CENELEC-ETSI 2012) this corresponds to the information layer.

Service layer

The classifier **Service Layer** describes the communication method and the protocol that is used for an operation method. In the SGAM, this corresponds to the communication layer that defines the protocols and mechanisms for the interoperable exchange of information between components (CEN-CENELEC-ETSI 2012). This classifier equals the levels transport, network, and link introduced in Kurose and Ross (2013). In Knapp and Langill (2015) an overview of communication topologies in industrial networks is provided, that can be applied for power system operation systems as well.

Technology

The **Technology** classifier represents the physical layer of the OSI model as well as the physical layer according to Kurose and Ross (2013) or part of the component layer in the SGAM (CEN-CENELEC-ETSI 2012). It defines the transport medium, whether the communication is wireless or wired, and which particular realization is used as well as the type of technology and the physical topology of the connected devices. In Gungor et al. (2011) an overview of commonly used communication technologies suitable for smart grid solutions is presented. Ethernet and power line communication are frequently used, but audio frequency ripple control is widely operated as well. This classifier implicates the costs for the necessary communication hardware, which is important for a techno-economic assessment.

Application

In this section we present an application example for the classifiers. Four different smart grid solutions are analyzed according to the classifiers introduced in "Assessment clas-

Table 2 Analysis of smart grid solutions according to the Assessment Classifiers

	"Distributed multiple agent system" (Zhang et al. 2014)	"Central Q-Management" (Wang et al. 2015)	"LV-Grid automation system" (Oerter and Neusel-Lange 2014; SAG GmbH 2013)	"Local Q(V) droop control" (Stetz 2014; Stetz et al. 2014)
TRL	3	4	9	9
Objective(s)	- Active power loss minimization - Voltage profile optimization	- Reactive power provision at the interface between two voltage levels - Compliance with voltage band at local buses of generators	- Compliance with voltage band - Control utilization rate of components	- Compliance with voltage band at local bus of a generator
Operation architecture	Distributed	Hierarchical (Comination of central and local)	Decentralized	Local
Input	- Local measurement of voltage magnitude and from neighboring operation units - Voltage phase difference between neighboring operation units	- Voltage magnitude at local buses - Reactive power set point at grid interface - Reactive power measurement at the grid interface	- Voltage magnitude - Line current - Active and reactive power flow - Phase angles - Active and reactive power operation points of generators	- Local voltage magnitude measurement at coupling point of generator
Control variables	- Transformer tap set point - Voltage magnitude set point of generators - Reactive power set point for capacitor banks	- Q(V) characteristic - Reactive power set points of generators	- Transformer tap set point - Power factor set points of generators and storage - Active power set points of generators and loads	- Reactive power set point of generator
Method	Distributed subgradient algorithm	Characteristic curve	3-stage control model including sensitivity analysis with grid state identification	Droop control
Communication				
Information flow	Between topological neighboring agents	From HV-level control center to RTU, from RTU to generators	Between the LV "monitoring and control system" and the sensors and actuators	No communication
Service layer	Peer-to-peer	Client - server	Client - server	No communication
Technology	Power line	Radio control	Power line within the low voltage grid GPRS with the control center	No communication

sifier" section (see Table 2). The aim is a general comparison of different reactive power management solutions.

This is accomplished via publications that each describe a power system operation method. These four solutions address different aspects of future smart grids and have varying technology readiness levels (TRL) (Technology readiness levels (TRL) 2014) and communication requirements. Such technology readiness levels allow for the evaluation of the maturity of a solution regarding its possible introduction on the market. The first solution is taken from the work published by Zhang et al. (2014). Its objective is the optimal reactive power control. The second solution is described in Wang et al. (2015). It proposes a "central" reactive power management that is able to provide reactive power at the interface between two voltage levels, which application in a field test is planned. According to the classification in "Assessment classifier" section this solution has a hierarchical operation architecture. The third solution has been commercialized and describes a LV grid automation system (Oerter and Neusel-Lange 2014; SAG GmbH 2013). The fourth solution is the Q(V) droop control, which is deployed in state-of-the-art PV-inverters and windparks. A description can be found in Stetz (2014). Table 2 analyzes these four solutions according to the presented classification method.

All the solutions can be called "reactive power management," but they differ in their characteristics. Their common objective is the compliance with the voltage band in the respective grid area, but some of them have additional objectives. Their operation architectures are different, even though they share a common objective and use the same control variables. The common control variable of the four solutions is the reactive power of the generators. The input variable for all the solutions is the voltage magnitude. However, the number of available voltage measurements varies. For the local Q(V) droop control, every local operation unit only measures its local voltage magnitude, whereas other solutions can rely on the voltage magnitude from neighboring buses or even the complete grid state. The communication for the four approaches ranges from client-server architectures to peer-to-peer approaches, but the Q(V) droop control does not require communication.

Based on the presented comparison, further investigations can be conducted, such as a techno-economic assessment. However, it is important to keep in mind how comparable solutions are in terms of the evaluated objective. If the compliance with the voltage band should be evaluated, one must, for example, neglect or disable the ability of the central Q-management to provide reactive power at the connection point to the higher-level grid.

For the single objective of compliance with the voltage band in a radial network, the local Q(V) control is an appropriate approach, as it does not require communication. For more complex grids, such as meshed grids, this may not be suitable, and a more complex solution like the LV-grid-automation system (Oerter and Neusel-Lange 2014; SAG GmbH 2013) or the central Q-Management (Wang et al. 2015) would be more fitting. However, it is important to note that these two methods rely on a client-server architecture. If we add resilience to the evaluation criteria, the distributed multiple agent system might be a better choice. Additionally, if we add economic aspects to the assessment, it is crucial to consider the ICT costs. In Zhang et al. (2014), it is claimed that "no powerful centralized processor" is needed. However, the relation of the costs for the simple hardware for the node agents to the costs of such a centralized unit - as necessary for the central Q-Management or the LV-Grid automation system - must be evaluated. However, this is highly grid-specific, as the costs for this peer-to-peer solution scale with the number of included operation units, whereas the bulk cost for a central solution is the central operation unit, and in relation to this, the costs for additional units are low.

Conclusion

This paper proposes definitions for the use of descriptive terms for the classification of smart grid solutions. These definitions are further used as a comprehensive way to compare different smart grid solutions on a structural basis. For this structural assessment, this paper presents classifiers that cover all important technical aspects of a possible solution - particularly the communication requirements. This approach can be used to support business-related decisions that need to consider not only the quality of the possible solution but also the infrastructure and necessary requirements. This contribution is also useful for other researchers to clearly categorize possible existing solutions and to highlight the degree of novelty of their own approach. Thus, it provides a tool for in-depth comparisons between power system operation methods. It further facilitates advanced investigations such as those regarding the resilience of the solutions that depend on the interaction between the various aspects or techno-economic evaluations.

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Authors' contributions
Ms. Wenderoth developed the basic idea of the separation into Objective(s), Operation Architecture, and Communication and contributed to the background research. Ms. Drayer examined System Architectures in neighboring Disciplines and developed the detailed version of the Assessment classifiers. The classifier Communication was developed by Ms. Drayer and Mr. Niedermeier equally. All of the authors have read and approved the final manuscript.

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Author details
[1]Department Grid Planning and Grid Operation, Fraunhofer IEE, Kassel, Germany. [2]Department of Energy Management and Power System Operation, University of Kassel, Kassel, Germany. [3]Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer Sheva, Israel. [4]Department of Measurement and Control, University of Kassel, Kassel, Germany. [5]Chair of Computer Networks and Computer Communications, University of Passau, Passau, Germany.

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