Online Reconfigurable Control Software for IEDs

Thomas Strasser, *Senior Member, IEEE*, Filip Andrén, *Member, IEEE*, Felix Lehfuss, Matthias Stifter, *Member, IEEE*, and Peter Palensky, *Senior Member, IEEE*

***Abstract*—The future energy system has to satisfy a continuously growing demand for electricity and to reduce greenhouse gas emissions. Fulfilling such diverse needs requires the integration of renewable energy resources on a large scale. However, the existing information and communication infrastructure controlling the corresponding power grids and components is not directly designed to master the ever increasing complexity. An upcoming requirement is the need for the functional adaption of the control systems during operation. The main aim of this article is to discuss and analyze requirements as well as to introduce a standard-compliant concept for a reconfigurable software architecture used in intelligent electronic devices for distributed and renewable energy resources. A simulation case study shows the applicability of this approach. A secure adaptation of the functional structure and the corresponding algorithms in device controllers can substantially contribute to a more efficient energy system, while at the same time responding to future needs.**

***Index Terms*—Communication, distributed energy resources, IEC 61499, IEC 61850, intelligent electronic devices (IEDs), reconfigurable control software, simulation, smart grids.**

I. Introduction

THE future power grids have to integrate a higher amount of renewable energy resources (RES) and distributed energy resources (DER) in order to cope with a growing electricity demand, while at the same time trying to reduce the emission of greenhouse gases [1]–[5]. Moreover, distribution system operators (DSO) will be confronted with new challenges, due to the highly dynamic and stochastic behavior of RES (e.g., photovoltaic systems and wind turbines) as well as controllable loads (e.g., electric vehicles and smart buildings). Advanced information and communication technologies (ICTs) and control systems are often seen as a key solution addressing these challenges, by providing means for ancillary services and advanced demand side management concepts [6]–[8]. However, the ICT infrastructure of today's power grids is not designed to manage the upcoming complexity [9], [10].

Recent research results and developments of advanced control algorithms, ancillary services or demand side management concepts contribute to a smarter grid [11], [12]. However, even research cannot predict all possible needs of the future grid, leading to continuously new and improved services. At the moment there are no concepts for online-adaptations of the logical and functional behavior of existing DER devices available [13]. Consequently, a roll-out of new functionalities can today only be triggered through the explicit demand of grid standards. This will entail large investments for DSOs, device operators or customers. One example from practice is the 50.2-Hz PV inverter problem in Germany [14] (for details see Section III-A). Moreover, ICT solutions and standards for the power and energy domain capable to handle the online-adaptation of DER unit functions are missing.

For the information exchange between intelligent electronic devices (IED) the IEC 61850 standard for power utility automation is widely accepted in the Smart Grids framework [6], [15]–[17]. Originally developed for substation automation, IEC 61850 has been enlarged to cover also power utility equipment. Using this standard also for DER units from different vendors a higher degree of interoperability is achievable [18]–[20]. The standardized access to DER device functions (e.g., control or ancillary services for inverter-based DERs)—covered by IEC 61850-90-7—allows an advanced power systems management which is important for DSOs [6], [20]. However, for the functional adaptation at the device level, common services and interfaces are still missing in the IEC 61850 family. Such services as well as interfaces for DER units allowing a secure adaptation of the functional structure and algorithms can substantially contribute to a more efficient energy system, while at the same time fulfilling future needs.

This article is addressing this issue by analyzing reconfiguration requirements and providing a standard-compliant concept for the realization of functional adaptions in the control software of DER units. This approach is based on the IEC 61850 [15] interoperability standard for power utility automation and the IEC 61499 distributed control model [21]. It allows the online adaptation of device functions and provides an open, interoperable, and scalable solution addressing future needs in the Smart Grid domain. The work starts in Section II with an overview of related work, followed by the motivation and needs for functional adaptions of DER units in Section III. An analysis of reconfiguration possibilities in control systems is provided in Section IV, and the proposed standardized reconfigurable IED software architecture is given in Section V. In addition, Section VI provides an overview of a prototypical realization. A simulation-based validation example provides a first proof of the concept. Section VII concludes this paper.

II. Related Work

A. Smart Grid Activities, Control Systems, and Standards

As discussed in the introduction, the power distribution networks are currently being transformed into active grids

Manuscript received January 27, 2012; revised June 09, 2012; accepted February 07, 2013. Date of publication February 13, 2013; date of current version August 16, 2013. This work was supported by the Austrian Climate and Energy Fund and by the Austrian Research Promotion Agency (FFG) under the Project *"DG-EV-HIL"*. Paper no. TII-12-0032.

The authors are with the Energy Department, AIT Austrian Institute of Technology, 1210 Vienna, Austria (e-mail: thomas.strasser@ait.ac.at, thomas.i.strasser@ieee.org).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2013.2247045

supporting bidirectional energy exchange due to the upcoming high penetration of DERs. The implementation of such Smart Grids is an encouraging approach to overcome the limitations of today's electrical infrastructure [12]. However, these innovative grids require new components (e.g., inverters, smart meters, charging units, intelligent controllers) with advanced services (e.g., ancillary services) [1], [2], [5], [22] resulting in a very complex network of interconnected units exchanging information and energy. Such complex systems also need new validation and optimization methods [23], [24]. Intelligent Electronic Devices (IED) offer enhanced functionalities to manage the complex nature of Smart Grids. This issue is being addressed in several international standardization roadmaps[1] in order to guarantee an open and interoperable solution.

For the grid integration of IEDs communication, control, safety, and security issues have to be taken into account. In order to develop an interoperable solution, international standards have to be considered. Consequently, the development of grid components also needs to be aligned to these standards [25]. Several standardization bodies and organizations have analyzed this and as a result the usage of the following core standards for the development of Smart Grids is suggested [25], [26], [28]: *(i)* Reference Architecture (IEC 62357), *(ii)* CIM—Common Information Model (IEC 61970/61968), *(iii)* Power Systems Automation (IEC 61850), and *(iv)* Security (IEC 62351). In addition, the DKE roadmap [28] also advises IEC 61499 for distributed automation in Smart Grids.

Power utility automation is the core topic of IEC 61850 [15] which focuses on the harmonization of the information and data exchange between IEDs. This important standard covers the topics modeling, configuration and communication whereas the model data are provided in an object-oriented way [29]. In addition, IEC 61850-7-420 [19] and the new IEC 61850-90-7 [20]—which is currently under development—cover also DER related issues [18]. Since IEC 61850 mainly addresses interoperability topics, other concepts have to be taken into account for the implementation of functional logic (e.g., ancillary services). Promising approaches from the automation domain that can be applied are the Programmable Logic Controller (PLC) standard IEC 61131-3 [30] or the IEC 61499 [21] reference model for distributed control. IEC 61131-3 was especially developed for centralized PLCs whereas IEC 61499 was defined as a methodology for modeling open distributed Industrial-Process Measurement and Control Systems (IPMCS) in a vendor-independent way. Therefore this method fulfills the fundamental requirements of open distributed control systems [31]–[33]. Moreover, IEC 61499 has even more ambitious objectives like the *(i)* portability of automation projects, *(ii)* (re-)configurability of distributed devices by multiple software tools, and *(iii)* interoperability of control devices from different vendors [21], [32], [33].

A major difference between IEC 61131-3 and IEC 61499 is the execution model. The first one supports a cyclic execution of software elements whereas in the second one Function Blocks (FB) are initiated by events in order to allow the asynchronous execution of control software [33], [34]. Communication networks and protocols are not directly in the scope of IEC 61499 but their services can be encapsulated and represented as communication Service Interface FBs (SIFB).

The usage of IEC 61499 for energy systems was firstly demonstrated by Hegny *et al.* [35]. Moreover, the implementation of IEC 61850 Logical Nodes (LN) and its implementation with IEC 61499 for Smart Grids has already been reported by Higgins *et al.* [36], Vyatkin *et al.* [37], and Zhu *et al.* [13].

B. Simulation Methods for Smart Grids Development

The importance of simulation methods for Smart Grid developments has already been discussed by Podmore and Robinson [38] and Facchinetti *et al.* [39]. In this area, real-world tests for the validation of control functions and IED implementations are often hardly possible or costly. In order to have realistic validation setups, real-time simulation and Hardware-in-the-Loop (HIL) tests are promising methods during the design and implementation phase. They have shown several advantages over pure off-line/software simulations or pure hardware tests. Successful examples for the validation of automation functions have already been demonstrated in industrial areas like energy, automotive, aerospace, and manufacturing [40]–[42].

For the power and energy domain HIL can be separated into two methods: the traditional HIL setup is referred to as Controller-Hardware-in-the-Loop (CHIL) where typically the Hardware-under-Test has a low power rating. Steurer *et al.* [42] describe an approach applying the CHIL method in power systems for validating control functions, whereas the simulation of the grid physics is implemented in a real-time simulator and the control algorithms are executed on real controllers. In addition, a newer approach has attracted a lot of interest lately—the Power-Hardware-in-the-Loop (PHIL) method. PHIL uses a power amplifying interface to convert signals from the signal to the power level and thereby expands the application field of HIL simulations massively [42].

C. Reconfigurable Systems and Software

Reconfiguration of software units has been discussed many times, for instance by Kramer *et al.* [43] or Xu *et al.* [44]. Within the scope of this article adaptation is described best as altering a control system's function in order to meet changing requirements. A quite simple adaptation is to stop current operation, apply all necessary changes to the system and restart the desired operation again. This is called basic reconfiguration. In power grids this simple reconfiguration approach will not work since availability and maintaining power quality are crucial issues. The opposite of basic reconfiguration is termed dynamic or online reconfiguration where the change of software units during their execution is possible [31], [45].

Especially in distributed systems where various devices from different vendors are working together, a standard-compliant approach for the adaptation of control functions is necessary. It is proven that the usage of the IEC 61499 reference model provides a very good basis for the dynamic adaptation of control functions in the manufacturing domain [31], [33]. In the power and energy domain this issue was only reported by Villa *et al.* [46] whereas mainly high-level management functions are

[1]e.g., IEC Smart Grids standardization roadmap [25], NIST framework for Smart Grids interoperability [26], IEEE Guide for Smart Grid Interoperability [27], DKE German standardization roadmap for Smart Grids [28]

addressed. Applying software reconfiguration in power utility automation, especially for IEDs—which is covered by this article—was only mentioned as future requirement by Zhu *et al.* [13] so far.

III. Smart Grids: Permanently Changing Systems

A. Motivation, Main Idea, and Future Needs

The future electric energy system is characterized by the integration of a high amount of RES/DER which can cause bidirectional energy flow [2], [3], [11]. Moreover, the possibility to manage and control loads (e.g., load shedding, load shifting) enables additional flexibility which is necessary to master the high complexity of Smart Grids. New grid components like storages or moveable resources (e.g., electric vehicles) can be considered either as load (charging the battery) or as generator (providing electric energy to the grid). Their integration will increase the need for more intelligent methods to handle these new devices. The electrical energy system has already a complex nature because of the shared responsibilities between different players (e.g., energy suppliers, energy trading organizations, utilities, customers, regulators) with their individual interests and aims. These roles can be expected to be even more complex and diverse in the future due to a higher number of players like prosumers or charging service providers. Therefore, new methods regarding control, communication, management, or grid diagnosis must be both adaptable to changing, yet unknown, system requirements (i.e., physical and functional) and enable interoperability between players. This leads to requirements regarding reconfiguration as well as the necessity to align the new methods to international standards and roadmaps.

1) Physical Adaptations: The increase of distributed generation or electric vehicles may trigger the need for more or even dynamic physical reconfiguration of the electrical grid in the future [47], [48]. Topology changes through switching actions or physical changes in the network through the introduction of new components and devices (e.g., cables, storages, active filters) can be examples of measures to ensure grid stability.

2) Logical and Functional Adaptations: The transition towards a Smart Grid is rather achieved with the use of control and communication methods than with physical adaptation. Core components in the grid have a supposed life-time of more than 20 years making it challenging to keep their functionality up to date. In recent years, ancillary services for medium and low-voltage grids have received a higher focus in projects and grid-interconnection codes [49], [50].

These new ancillary services sometimes also require adaptations to already installed components. One example where adaptations are necessary is the 50.2 Hz problem in Germany, which is caused by the automatic disconnection of PV systems in case of over-frequency. With a PV generation capacity of about 30 GW this can heavily disrupt the stability of the grid. To overcome this problem all new and installed generators must be upgraded to be compliant with the new guidelines [49]–[51]. This upgrade affects PV inverter producers, grid operators, and customers and is estimated to cost up to 175 million Euro during the next years [14]. Such expensive upgrade processes can be

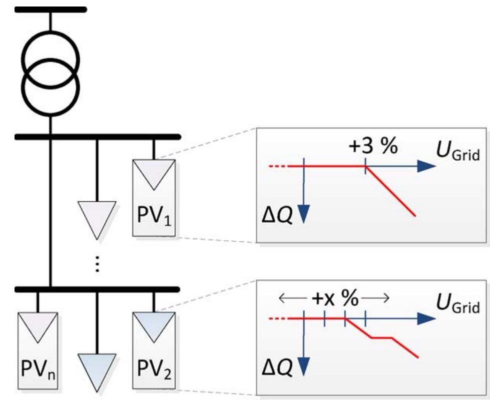


Fig. 1. Example with newer PV units providing ancillary services [49], [50].

improved and made more cost-effective through flexible reconfiguration and adaptation methods with standardized interfaces. Due to the future increase in DER components it might be even more important to use different operation strategies, depending on, for example the installation location of the component in the grid. Such an example is depicted in Fig. 1, where PV_1 and PV_2 have implemented different voltage control strategies.

Ancillary services are not the only example where the future functions in the Smart Grid and their corresponding devices are changing. Communication (e.g., new data models, additional communication channels), management functionality (e.g., new energy markets [52], or micro-grid/islanding functionality), as well as diagnostics/monitoring services are other examples where the requirements have to be met . Therefore, this paper focuses mainly on a standard-based method to handle functional adaptation of control devices in a changing Smart Grid area.

In summary, the future electric energy system will be more flexible and adaptable as today. Since the grid topology, the components, and their functions are changing over its life-time, appropriate management approaches are required. Especially on the device-level, reconfiguration of control functions would provide a significant contribution. Unfortunately, capturing these benefits today is impeded by a lack of common services and the use of proprietary controller systems [13]. However, there are no thorough investigation nor corresponding research results available in the literature addressing IED function adaptation. Moreover, software reconfiguration possibilities for IEDs are currently missing in corresponding standards.

B. Functional Adaptations: Use Cases and Requirements

This contribution covers the online reconfiguration of IED functions in DER units. Firstly, potential use cases addressing adaptation scenarios are presented. Table I provides a brief overview of the most important ones. It has to be noted that, being outside of this work, regulatory issues are not covered.

Taking these use cases into account Table II provides an overview of the derived, most important requirements for functional adaptions in IEDs during operation.

Especially the fulfillment of “Standard Compliance” and “Dynamic Adaptation” is in the scope of the software reconfiguration concept for DER units introduced later on.

TABLE I
BRIEF OVERVIEW OF FUNCTIONAL ADAPTATION USE CASES.

Use Case	Description
Parameter adaptation	The parameter adaptation of IED control functions is the simplest use case. For example, the parameters of a voltage or frequency control algorithm of a DER unit have to be adjusted for optimization purposes [49], [50].
New function(s)	From today's point of view it is nearly impossible to address all future needs related to IED realization. The addition of new control functionalities is therefore an essential future feature [13]. For example, in Germany about 15 GW power is produced from PV systems today. The 50.2 Hz problem issue is a well known fact because it is nearly impossible in DERs to update control functions and parameters remotely today [49], [50].
Function update	Due to changed grid conditions an update of control functions in IEDs (e.g., ancillary services) would be necessary for optimization purposes. An update could also cause the deletion of a function.

TABLE II
BRIEF OVERVIEW OF DERIVED RECONFIGURATION REQUIREMENTS.

Requirement	Description
Standard Compliance	A standardized realization of IEDs is essential in order to support the online reconfiguration of control functions in a network of DERs from different vendors. Open and extensible software interfaces are required.
Dynamic Adaptation	The reconfiguration of functions during IED operation should be possible. The functionality and availability of the electric energy system has to be guaranteed.
Platform Independence	The dynamic reconfiguration of the control functions in a network of heterogeneous IEDs requires a platform independent software realization.
Scalability	Online reconfiguration should work for one but also for various IEDs. In addition, the adaptation of one function as well as of several ones should be supported.
Safety & Security	Safety and security rules and domain-standards should be supported during reconfiguration. Formal validation approaches should be considered in order to allow the development of safe and secure solutions.

IV. ANALYSIS OF RECONFIGURATION POSSIBILITIES IN CONTROL SYSTEMS FOR SMART GRID COMPONENTS

As motivated in the previous section the adaptation of IED logic will be a future necessity for Smart Grids [13]. Since automation functions in safety-critical systems are affected, proper design and implementation methods are required. A lot of different approaches which address the online adaption of control functions are possible [31] (see Section II-C). Only few of them are suitable in a Smart Grid environment fulfilling IED interoperability and communication requirements. From this point of view the most important approach to model the data and information exchange between control, protection and measurement services is the IEC 61850 model. Since it only covers interface specifications and high-level communication patterns proper implementation concepts are required. From the control point of view the most important solutions are the PLC-based approach IEC 61131-3 and the IEC 61499 reference model for distributed automation.

Both approaches support the dynamic reconfiguration of control functions as shown in Table III. IEC 61131-3 and corresponding implementations normally support the on-line-exchange of software modules but not in a standardized way. Such a support is being handled individually by a particular implementation which is suitable in a homogenous hardware/software environment from one vendor[2]. Taking into account the electric energy domain where a lot of devices from different vendors are in use and which are owned by different players (e.g., power plant operators, grid operators, customers) the concepts provided by IEC 61131-3 might be not enough. In a changing environment—such as in the future Smart Grids—a standardized reconfiguration interface is necessary.

TABLE III
OVERVIEW OF IEC 61131-3 & IEC 61499 RECONFIGURATION SERVICES.

Reconfiguration Services	IEC 61131	IEC 61499
On-line control function adaptation	+	+
Standardized reconfiguration interface	–	+
Distributed functional adaptions	~	+
Reconfiguration tasks for online changes	~	+
Platform-independent reconfiguration tasks	–	+
Formal representation of reconfiguration tasks	~	+

Such needs have already been addressed during the development of IEC 61499. In general, it provides a standardized management model with corresponding (re-)configuration commands [31], [33]. Moreover, due to its component-oriented and event-driven architecture a reconfiguration at the FB level is possible. It can also be considered as executable model which brings the specification and implementation of applications closer together [33]. With the separation of the application and the hardware description as well as the corresponding mapping model a platform-independent realization of control logic becomes possible. Another benefit is the fact that the corresponding elements defined in IEC 61499 provide a formal model and software description method [53]. This allows the usage of verification technologies to improve the dependability of the control systems and to satisfy safety requirements [33]. This also means that a formal description as well as the corresponding formal verification of reconfiguration tasks [54] in Smart Grids can be performed with IEC 61499. It is an essential benefit using such an approach for Smart Grids in order to guarantee their availability and functionality.

In order to fulfill the main requirements as explained above a distributed control environment based on the IEC 61850 and IEC 61499 standards supporting the online-change of functional logic in IEDs is proposed. This combination provides a reference architecture for future automation and control technology enabling the possibility to adapt IED logic to fulfill future requirements in the power and energy domain.

V. RECONFIGURABLE CONTROL INTERFACE FOR IEDS

A. Concept in General: IEC 61850/IEC 61499 Compliance

The conformity to IEC 61850 for networked DER controllers is almost a must in today's power grids [25]. Since IEC 61850 only specifies the function interfaces an integration with IEC 61499 seems promising. This approach has already been proven as a way of maintaining a consistent information model throughout the design for Smart Grids [13], [36], [37].

[2]Such a scenario is typical for the manufacturing area.

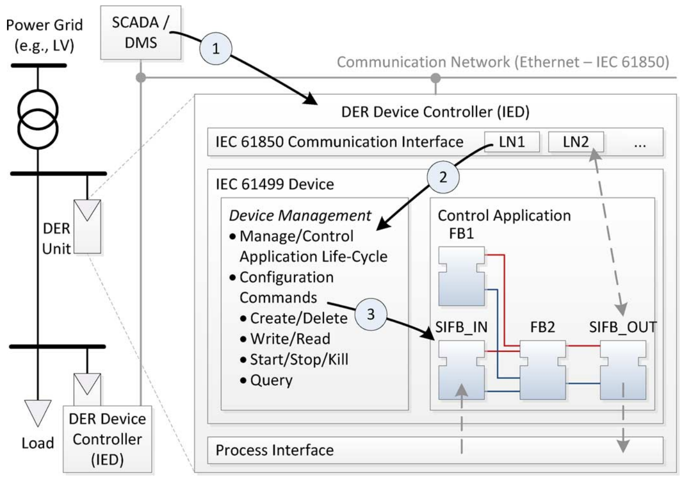


Fig. 2. Standard-compliant IED specification with IEC 61850/IEC 61499.

As discussed in Section III, the future energy system has to cope with changing requirements during its life-time. Therefore, adaptation of control functions and services—especially during operation—become an important issue in the future. The introduced control architecture based on IEC 61850 and IEC 61499 (see Fig. 2) supports the online reconfiguration of functions, services and applications. This is achieved through the ability to adapt the LN specification in IEC 61850 and the management model in IEC 61499. Therefore, a DER device controller has to implement a device management.

The IEC 61850 Logical Device (LD) and Logical Node (LN) specifications are implemented using the IEC 61499 device and FB model. The encapsulation of these control algorithms and communication services into IEC 61499 elements results in a modular and reusable implementation. Such a modular concept also allows an easy adaptation and reconfiguration of control functions and services. Fig. 2 provides an overview of the proposed standard-compliant realization supporting online reconfiguration. Each LD has a communication interface in order to communicate with the Supervisory Control and Data Acquisition System (SCADA)/Distribution Management System (DMS)[3] of the Distribution System Operator (DSO) and with other devices. In addition, the communication interface provides a standard-compliant access point in order to manage the life-cycle of the control functions, services and applications of the corresponding IED. The IEC 61499 device management model is responsible for this task. The reconfiguration possibilities are discussed below.

An important part of the above provided concept is the availability of an IEC 61499 FB library for the implementation of IEC 61850 LNs in DER devices. Such a FB library should contain general IEC 61850 LNs (e.g., `GGIO`, `XCBR`, `GAPC`) and special LNs for IEC 61850 DER functions, such as for DG (e.g., `DGEN`, `FPID`), DC/AC converters (e.g., `ZINV`, `ZRCT`), DC switches (e.g., `CSWI`, `XSWI`), PV inverters (e.g., `DPVM`, `DVPA`), physical measurements (e.g., `STMP`, `MPRS`) and so on. Moreover, the IEC 61850 Abstract Communication Service Interface (ACSI) (e.g., Client/Server, Peer-to-Peer, time synchronization, file transfers) should also be encapsulated into special IEC 61499 communication SIFBs. Together with a set of additional FBs accessing DER device I/Os, a powerful standard-compliant control library can be derived. Usually such services are executed on embedded hardware—as part of the DER devices—with limited capabilities (i.e., limited computation power, low amount of memory, etc.). Therefore, a crucial point is the lightweight implementation of the control functions and services on the resource limited hardware.

LDRC		
Data object name	Common data class	Explanation
Common LN information		
Status information		
NewCnfgValid	SPS	New configuration is valid
CurCnfg	VSS	Current configuration (name of SCL file)
Settings		
NewCnfgFileName	VSG	New configuration (name of SCL file)
NewCnfgStr	VSG	New configuration from string
CnfgSrc	SPG	Use file or string as configuration source (TRUE/FALSE = use string/use file)
Controls		
ReCnfg	SPC	Apply new configuration

Fig. 3. The new IEC 61850 LN "Device Reconfiguration" (LDRC).

B. *IEC 61850 Reconfiguration Interface for Online Changes*

In order to avoid to have a separate interface for the IEC 61850 interoperability and for the reconfiguration of control functions using the IEC 61499 management model, a deep integration is preferred. Since IEC 61850 does not provide a reconfiguration interface a new "Logical Device Re-Configuration" LN (`LDRC`) is introduced [15]. It uses the ACSI service for file transfer. The LN specification is given in Fig. 3.

According to Step 1 in Fig. 2 an IEC 61850 client (e.g., SCADA, DMS) can deploy a modified SCL file[4] for functional adaptions to a particular IED. It has to be noted here that it is also possible to deploy the IEC 61499-compliant implementation (FBs) of new logical functions (LNs) within the SCL description. Since the IEC 61499 definition of FBs is carried out in XML this information can be included using the `Private` tag in the SCL file reducing the need for separated communication interfaces (see Listing 1).

Listing 1. Sketch of the IEC 61499 FB definition in IEC 61850 SCL-syntax

```
< LN lnClass="GGIO" … >
< Private type="IEC61499">< ?xml version="1.0"
encoding="UTF–8"? >
< !DOCTYPE FBType SYSTEM
"http://LibraryElement.dtd" >
< FBType … > … < /FBType >
< /Private >
< /LN >
```

During Step 2 the IED has to analyze the changes in the SCL file and to derive reconfiguration request for the IEC 61499 device management. It usually supports 8 configuration commands (i.e, `CREATE`, `DELETE`, `WRITE`, `READ`, `START`, `STOP`, `KILL`,

[3]Mainly power distribution grids are in the focus of this work.

[4]XML-based IEC 61850 Substation Configuration Language (SCL) file.

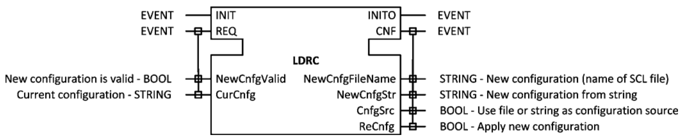


Fig. 4. The IEC 61850 server implementation of LDRC using IEC 61499.

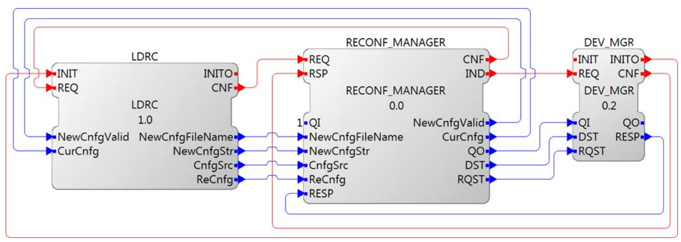


Fig. 5. IEC 61499 implementation of the reconfiguration interface.

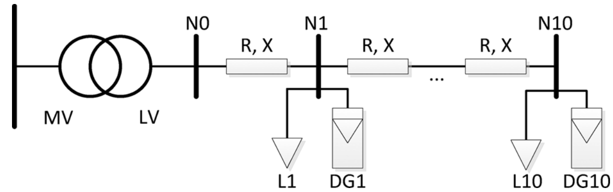


Fig. 6. Low-voltage feeder used in control logic reconfiguration test case.

QUERY) according to the management model which are used controlling the life-cycle of FBs and control applications. In Step 3 the device management executes (re-)configuration requests using the configuration commands and therefore modifies the IEC 61499 implementation of LNs.

C. IEC 61499 Realization of the Reconfiguration Interface

For the implementation of the reconfiguration approach the IEC 61499 language is used as proposed in Section V-A. The device reconfiguration LN LDRC also has to be implemented as an IEC 61499 FB. The following Fig. 4 shows the corresponding FB interface. It implements the IEC 61850 file transfer and provides either a full SCL description or a configuration string to the IEC 61499 world.

The interface to the IEC 61499 device management is usually provided via special SIFB, the DEV_MGR FB [21], [32], [33]. This management SIFB receives requests and triggers the device management for its execution. Since the LDRC FB provides either the full SCL description or parts of it (i.e., via the configuration string) a direct connection to the DEV_MGR FB does not make sense. Some transformation FB is needed to transform SCL descriptions into (re-)configuration commands to the device management. For this purpose a special FB—called RECONF_MANAGER—is introduced. The resulting IEC 61499 FB network is shown in Fig. 5. In case of a reconfiguration request from a client (e.g., triggered by a file transfer) the RECONF_MANAGER FB receives an IEC 61850 SCL definition on the input side and transforms it into a syntax that is interpretable by the DEV_MGR FB. Moreover, this reconfiguration FB also has the ability to request information on the running IEC 61499 control application(s). Based on the desired and the existing IED configuration it is possible to derive the necessary reconfiguration commands to adapt control logic implemented via IEC 61499 FBs during operation.

VI. Implementation, Validation and Results

A. Prototypical Implementation

To prove the feasibility of the presented approach a prototype was made. The IEC 61499 open source project 4DIAC was used for the design of the control applications, providing an engineering environment and a runtime system for different platforms (e.g., embedded and PC-based) [55]. For the IEC 61850 communication services a commercially available stack has been integrated into 4DIAC. Using this environment, the IED reconfiguration interface—as proposed in Section V-B consisting of the FBs LDRC, RECONF_MANAGER, and DEV_MGR—has been implemented. Moreover, several IEC 61499 FBs representing IEC 61850 LNs (described in Section V-A) are also available in the 4DIAC environment allowing the testing of functional adaptions in IEDs.

B. Validation by Simulation

For the validation of the proposed reconfiguration concept a combination of a real and a simulated environment has been used, since it is usually not possible to test such methods in real grids. For this purpose the DIgSILENT/PowerFactory power systems simulator was used representing the distribution grid. The IED logic was implemented according to the proposed IEC 61850/IEC 61499 integration including the reconfiguration interface. Since PowerFactory does not have a direct support for IEC 61850 some glue logic using OPC was necessary to allow PowerFactory and 4DIAC to communicate with each other. It was not necessary to analyze the dynamic behavior of the grid components, thus no transient simulation was needed and consequently the usage of power profiles for loads and DERs with a few seconds time resolutions were sufficient. Further, OPC as communication interface with a time delay of milliseconds is motivated. Moreover, since a time resolution of a few milliseconds up to seconds is usually sufficient for the IED implementation no further timing restrictions arise for this kind of simulation experiment.

C. Performed Test and Results

1) Scenario Description: In order to validate the adaptation concept a synthetic reconfiguration example is introduced (see Fig. 6). It covers the functional adaptation of a PV unit in a Low-Voltage (LV) feeder to solve an over-voltage problem.

The LV feeder consists of several loads (i.e., L_n) and PV units (PV_n) controlled by the proposed IEC 61850/IEC 61499 concept. The corresponding reconfiguration scenario, shown in Fig. 7, is divided into the following four phases:

1) In the initial state of the scenario ten households along a feeder are equipped with a PV unit where five of them are in the operational mode and the distribution grid does not experience any voltage problems.
2) A sixth PV unit is turned into operation which causes the voltage in the feeder to rise above the allowed limit during clear sunny days.

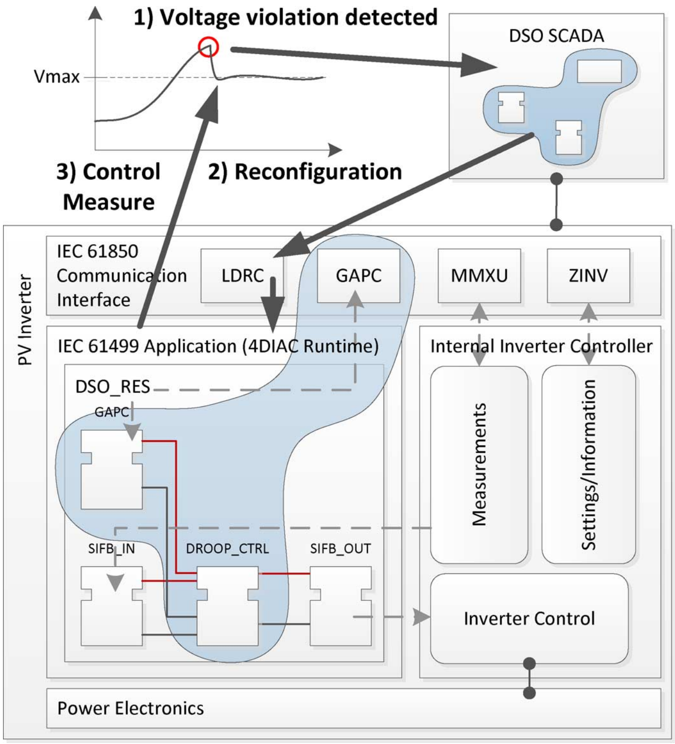


Fig. 7. Example of a PV inverter control function adaptation.

3) When the over-voltage is detected the DSO reconfigures the PV inverter's control software with a droop control function for active and reactive power.
4) The droop control helps to lower the grid voltage.

2) Inverter Droop Control: A detailed description of the droop control used in this test case can be found for example in [56], [57]. Frequency and voltage over a line are dependent on the active and reactive power flowing through the line

$$\sin\delta = \frac{XP_A - RQ_A}{U_A U_B}, \; U_A - U_B\cos\delta = \frac{RP_A + XQ_A}{U_A} \quad (1)$$

where δ is the power angle and U_A and U_B represent voltage at connection point A and B respectively. P_A and Q_A are the active and reactive power produced at connection point A. Normally δ is assumed small and $X \gg R$ resulting in

$$\delta \simeq \frac{XP_A}{U_A U_B}, \quad U_A - U_B \simeq \frac{XQ_A}{U_A}. \quad (2)$$

This test case focuses on the grid voltage, i.e., (2) and since a LV grid is studied the impact of the active power on the grid voltage cannot be neglected. This means the voltage can be regulated through changes in P and Q

$$U_A - U_B = \frac{RP_A + XQ_A}{U_A} \quad (3)$$

where $R + jX$ denotes the grid impedance. In other words, it is possible to regulate the voltage of the grid by altering active and reactive power production by the PV unit. The droop control is represented by the DROOP_CTRL FB (see Fig. 7) and is deployed by the DSO to the PV IED during operation.

3) Power Network Modeling: The network used in the simulations is depicted in Fig. 6. It was implemented within DIgSILENT/PowerFactory where loads and DERs were modeled as positive and negative loads, respectively. Synthetic H0 load profiles were used for the loads and the consumption was scaled to 4000 kWh/year, representing a typical household with four people [58]. The Distributed Generator (DG) profiles are based on the measured generation from a 1 kWp PV array during a clear sunny day, representing an optimal situation seen from the generation point of view. In the test case it was assumed that all loads (L1–L10) are using the same H0 profile. For the DERs the following settings have been used in this test scenario: DG1–DG4, DG8: 2 kWp; DG5: 5 kWp; DG6–DG7, DG9–DG10: no generation. Between each node (N0–N10) a cable with an electrical impedance of $0.439 + j0.305\Omega$ was used. In this test case the DSO uses a voltage band between 0.95 and 1.05 p.u. The normal voltage limits for low voltage grids according to EN 50160 [59] dictates an allowed voltage magnitude variation of $\pm 10\%$ and an increase of the voltage affected by DG of 3%. However, the voltage limits used for this test case were chosen to allow a buffer in case of voltage violation which represents a real-world scenario. In this scenario, the transformer which connects the LV feeder with the medium voltage network is equipped with an off-load tap changer. Since the low-voltage ratio/tap is fixed and normally not changed afterwards, it is nearly impossible to make some adjustments because it is under load and the customers have to be cut off in the case of a tap change.

4) Test Case Definition: To simulate and validate the selected scenario each PV unit controller (i.e., DG1–DG10) implements the following three main parts, *(i)* an IEC 61850 compliant communication part, *(ii)* an IEC 61499 compliant DSO part and, *(iii)* an internal PV inverter control part, as shown in Fig. 7. The communication interface uses IEC 61850 and contains some LNs which remain constant providing measurements and (diagnostic) information about the PV inverter (e.g., a measurement LN MMXU, STMP and a PV inverter LN ZINV as depicted in Fig. 7). Using the SCL description it is possible for the DSO to reconfigure, respectively add LNs to the communication interface online, representing the IEC 61499 functions added to the DSO_RES.

The IEC 61499 compliant part executes a 4DIAC runtime environment where the DSO has access to one resource (DSO_RES). With the proposed IEC 61850/IEC 61499 reconfiguration interface control functions can be deployed to this resource and also reconfigured, if necessary (see Fig. 7). Some FBs are already provided in the DSO_RES by the PV inverter IED, namely one SIFB which provides measurements of V, P and Q at the Point of Common Coupling (PCC) between the PV inverter and the grid (SIFB_IN in Fig. 7) and one SIFB that has set points for P and Q (i.e., P_{set} and Q_{set}) as inputs to the internal inverter control (SIFB_OUT in Fig. 7). Using this approach the DSO can control the set points of P and Q, however the internal control of the inverter still has the final decision on how it will use these set points (e.g., limitations on power factor or maximum allowed active power curtailment). The last part

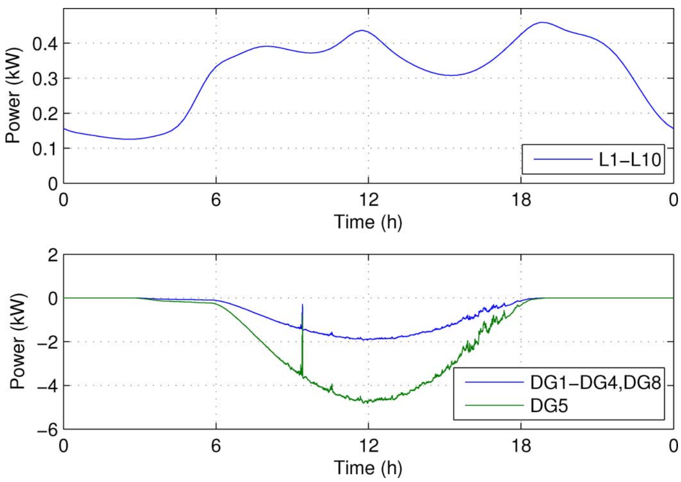


Fig. 8. Active power consumption and generation from loads and DGs.

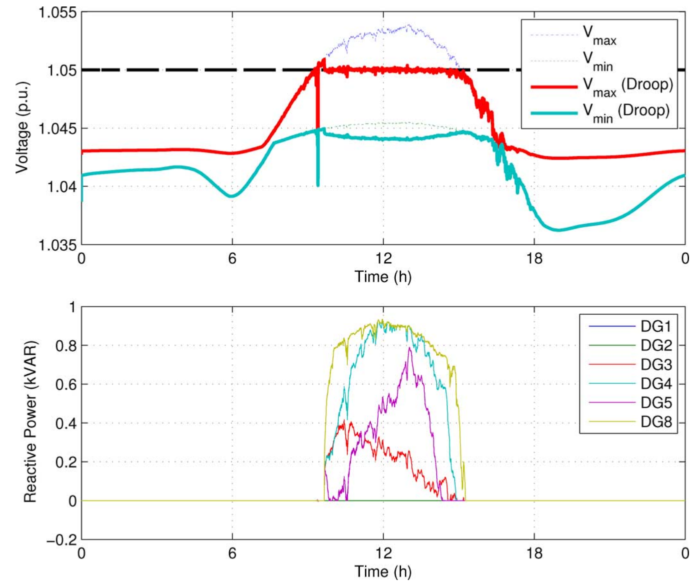


Fig. 9. Voltage band in feeder with DG5 connected and DGs reactive power.

is where the internal PV inverter control is executed. It controls the power electronics of the inverter and cannot be directly accessed by the DSO. This part can still be implemented using IEC 61499 or it can provide a standard-based interface, both options are possible.

Fig. 7 shows the reconfiguration scenario: In *Phase 1)* the DSO detects a voltage violation after DG55 is connected to the grid. To cope with this over-voltage the DSO downloads and activates a droop control to each of the DGs, *Phase 2)* (i.e., online adaption of the PV inverter's controller functions). This is done by the reconfiguration of the DSO_RES to include a droop control FB (DROOP_CTRL). A new LN is also added as a IEC 61850 representation of the new droop control; in Fig. 7 this is shown as a Generic Automatic Process Control LN (GAPC). As a connection between the IEC 61499 part and the communication interface a GAPC FB is also added to the DSO_RES. In *Phase 3)* the newly reconfigured PV inverter's controllers help to lower the voltage in the distribution grid.

5) Simulation Results: To test the above described adaptation scenario one day was simulated[5], where it is assumed that DG5 was connected just before the simulation starts. As already mentioned, there were no voltage violations before DG5 was connected. The active power profiles for the loads and the DGs in the feeder are depicted in Fig. 8. Using the proposed reconfiguration possibility the DSO can compensate for such an over-voltage by means of droop control in each PV inverter controller. To simplify matters, only voltage droops using reactive power were used and since the ratio $R/X \ll \infty$ the impact of Q is still considerable which also motivates this simplification. The resulting voltages together with the reactive power from DG1–DG8 are shown in Fig. 9. As reference, the system state without droop control is shown too.

When the over-voltage is detected the DSO initiates an online reconfiguration of the DSO_RES in each PV inverter IED, which happens around 10:00 AM (see Fig. 9). Each PV inverter IED receives the DROOP_CTRL FB and the LN GAPC, however depending on the voltage level at each inverter before the over-voltage occurs different voltage set points are used. Thus the PV inverter with highest voltage—in this case DG5—receives 1.05 as voltage set point, the inverter with the next highest voltage receives 1.049 and so on. Using this method not only DG8 contributes to the voltage reduction using reactive power. As shown in Fig. 9 the PV inverters manage to keep the voltage under the limit of 1.05 p.u. using the droop control.

VII. Conclusions

Since the future electric energy system has to integrate RES/DERs on a large scale proper management approaches and interoperability concepts are required. On the device level the IEC 61850 standard for power utility automation is widely accepted for Smart Grids fulfilling interoperability needs. Also the specification of IED functions for DERs—but not its implementation—is covered by this important standard.

In this article the need for the functional adaption on the device level was motivated and analyzed. Such a functionality could provide additional possibilities allowing DSOs a more flexible management and optimization of the power distribution grids with a large penetration of RES/DERs. The parameter adaption, the addition of new functions as well as the function update in IEDs have been identified as the main reconfiguration use cases. Moreover, a standard compliant and a dynamic adaptation of these IED functions, together with the platform independent realization, the scalability as well as the safe and secure realization, are seen as the most important future requirements for the operation of DERs in Smart Grids.

A reconfiguration interface in IEC 61850 is missing up to now. On the other hand the IEC 61499 reference model for distributed automation and control defines a FB language for the implementation of control functions in controllers as well as specifies a management interface and corresponding configuration commands which allows the realization of a reconfigurable control software. In order to implement such a concept an IEC

[5]A real-time execution of the DIgSILENT/PowerFactory model together with IEC 61850/IEC 61499 compliant PV IEDs was used as simulation setup.

61850 IED reconfiguration interface (i.e., LDRC LN) was introduced by this work to support the adaptation process in IEDs. This interface was combined with the device management possibilities of the IEC 61499 model. With this IEC 61850/IEC 61499 standard-compliant IED realization reconfigurability at the device level is achievable.

The proposed concept was prototypically implemented in an IEC 61499 controller software with IEC 61850 support. A first proof-of-concept with a simulated power distribution grid and the addition of a new droop control function in an IED has shown its applicability. The usage of this concept is not only restricted to DER devices, extensions to other grid components like storages, protection equipments (breakers, switches, etc.), or charging devices is also possible and recommended.

The future work will mainly focus on detailing the presented reconfiguration concept, on various CHIL simulation examples in the laboratory environment and the extension of the IEC 61499 FB library of IEC 61850 services for DER devices. It is also planned to implement the reconfigurable control software architecture in a PV inverter device controller. Moreover, an IEC 61499 compliance profile for reconfigurable IED control software in Smart Grids is planned for the future.

REFERENCES

[1] C. Cecati, C. Citro, A. Piccolo, and P. Siano, "Smart operation of wind turbines and diesel generators according to economic criteria," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4514–4525, Oct. 2011.

[2] M. Liserre, T. Sauter, and J. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 18–37, Jan. 2010.

[3] J. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Electric Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, 2007.

[4] A. Moreno-Munoz, V. Pallares-Lopez, J. G. de la Rosa, R. Real-Calvo, M. Gonzalez-Redondo, and I. Moreno-Garcia, "Embedding synchronized measurement technology for smart grid development," *IEEE Trans. Ind. Ind.*, vol. 9, no. 1, pp. 52–61, Feb. 2013.

[5] G. Spagnuolo, G. Petrone, S. Araujo, C. Cecati, E. Friis-Madsen, E. Gubia, D. Hissel, M. Jasinski, W. Knapp, M. Liserre, P. Rodriguez, R. Teodorescu, and P. Zacharias, "Renewable energy operation and conversion schemes: A summary of discussions during the seminar on renewable energy systems," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 38–51, Jan. 2010.

[6] B. Seal, "Standard Language Protocols for Photovoltaics and Storage Grid Integration" Electric Power Res. Inst., 2010.

[7] D. De Silva, X. Yu, D. Alahakoon, and G. Holmes, "A data mining framework for electricity consumption analysis from meter data," *IEEE Trans. Ind. Inf.*, vol. 7, no. 3, pp. 399–407, Aug. 2011.

[8] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Inf.*, vol. 7, no. 3, pp. 381–388, Aug. 2011.

[9] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.

[10] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. Hancke, "A survey on smart grid potential applications and communication requirements," *IEEE Trans. Ind. Inf.*, vol. 9, no. 1, pp. 28–42, Feb. 2013.

[11] "Smart Grid Insights," Int. Energy Agency, 2011.

[12] X. Yu, C. Cecati, T. Dillon, and M. Simões, "The new frontier of smart grids," *IEEE Ind. Electron. Mag.*, vol. 5, no. 3, pp. 49–63, Mar. 2011.

[13] L. Zhu, D. Shi, and X. Duan, "Standard function blocks for flexible IED in IEC 61850-based substation automation," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 1101–1110, May 2011.

[14] J. Bömer, K. Burges, P. Zolotarev, and J. Lechner, "Summary: Impact of large-scale distributed generation on network stability during over-frequency events & development of mitigation measures," Ecofys Germany GmbH; Inst. Combustion and Power Plant Technol., Univ. Stuttgart, 2011.

[15] *Communication Networks and Systems for Power Utility Automation*, IEC 61850, Int. Electrotech. Commission, 2010.

[16] G. M. Junior, E. Pellini, E. Senger, and R. Nakagomi, "IEC61850 based systems – Functional testing and interoperability issues," *IEEE Trans. Ind. Inf.*, vol. PP, no. 99, pp. 1–9, 2012.

[17] P. Parikh, T. Sidhu, and A. Shami, "A comprehensive investigation of wireless LAN for IEC 61850 based smart distribution substation applications," *IEEE Trans. Ind. Inf.*, vol. PP, no. 99, pp. 1–11, 2012.

[18] A. Apostolov, "Modeling systems with distributed generators in IEC 61850," in *Proc. Power Syst. Conf.*, 2009, pp. 1–6.

[19] *Communication Networks and Systems for Power Utility Automation – Part 7–420: Basic Communication Structure – Distributed Energy Resources Logical Nodes*, IEC 61850-7-420, Int. Electrotech. Commission, 2009.

[20] *Communication Networks and Systems for Power Utility Automation – Part 90–7: IEC 61850 Object Models for Photovoltaic, Storage, and Other DER Inverters*, Draft IEC 61850-90-7 TR, Int. Electrotechnical Commission, 2011.

[21] IEC 61499: Function Blocks International Electrotechnical Commission (IEC) Std., 2012.

[22] Q. Yang, J. Barria, and T. Green, "Communication infrastructures for distributed control of power distribution networks," *IEEE Trans. Ind. Inf.*, vol. 7, no. 2, pp. 316–327, May 2011.

[23] V. Calderaro, C. Hadjicostis, A. Piccolo, and P. Siano, "Failure identification in smart grids based on petri net modeling," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4613–4623, Oct. 2011.

[24] P. Siano, C. Cecati, H. Yu, and J. Kolbusz, "Real time operation of smart grids via fcn networks and optimal power flow," *IEEE Trans. Ind. Inf.*, vol. 8, no. 4, pp. 944–952, Nov. 2012.

[25] SMB Smart Grid Strategic Group (SG3), "IEC Smart Grid Standardization Roadmap" Int. Electrotechnical Commission, Geneva, Switzerland, Tech. Rep. Ed. 1.0, 2010.

[26] NIST Framework and Roadmap for Smart Grid Interoperability Standards Nat. Inst. Standards and Technol, U.S. Dept. of Commerce, Tech. Rep. NIST Publication 1108, 2010.

[27] *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*, , Oct. 2011, IEEE Std 2030-2011.

[28] "The German Standardisation Roadmap E-Energy/Smart Grid," Tech. Rep. German Commission for Electrical, Electronic & Information Technologies of DIN and VDE, Frankfurt, Germany, 2010.

[29] D. Ingram, P. Schaub, R. Taylor, and D. Campbell, "Performance analysis of IEC 61850 sampled value process bus networks," *IEEE Trans. Ind. Inf.*, vol. PP, no. 99, p. 1, 2012.

[30] IEC 61131-3: Programmable Controllers – Part 3: Programming Languages Int. Electrotechnical Commission (IEC) Std., 2003.

[31] R. Brennan, P. Vrba, P. Tichy, A. Zoitl, C. Sünder, T. Strasser, and V. Marík, "Developments in dynamic and intelligent reconfiguration of industrial automation," *Comput. Industry*, vol. 59, pp. 533–547, 2008.

[32] V. Vyatkin, "The IEC 61499 standard and its semantics," *IEEE Ind. Electron. Mag.*, vol. 3, no. 4, pp. 40–48, Mar. 2009.

[33] V. Vyatkin, "IEC 61499 as enabler of distributed and intelligent automation: State-of-the-art review," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 768–781, Nov. 2011.

[34] T. Strasser, A. Zoitl, J. Christensen, and C. Sünder, "Design and execution issues in IEC 61499 distributed automation and control systems," *IEEE Trans. Syst., Man, Cybernet., C, Applic. Rev.*, vol. 41, no. 1, pp. 41–51, Jan. 2011.

[35] I. Hegny, R. Holzer, G. Grabmair, A. Zoitl, F. Auinger, and E. Wahlmuller, "A distributed energy management approach for autonomous power supply systems," in *Proc. IEEE Int. Conf. Ind. Inf.*, 2007, pp. 1065–1070.

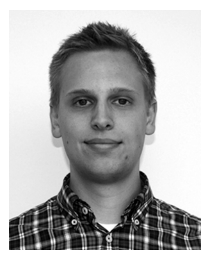
[36] N. Higgins, V. Vyatkin, N.-K. Nair, and K. Schwarz, "Distributed power system automation with IEC 61850, IEC 61499, and intelligent control," *IEEE Trans. Syst., Man, Cybernet., C, Applic. Rev.*, vol. 41, no. 1, pp. 81–92, Jan. 2011.

[37] G. Zhabelova and V. Vyatkin, "Multiagent smart grid automation architecture based on IEC 61850/61499 intelligent logical nodes," *IEEE Trans. Ind. Electron.*, vol. 59, no. 5, pp. 2351–2362, May 2012.
[38] R. Podmore and M. Robinson, "The role of simulators for smart grid development," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 205–212, Sep. 2010.
[39] T. Facchinetti and M. Della Vedova, "Real-time modeling for direct load control in cyber-physical power systems," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 689–698, Nov. 2011.
[40] C. Molitor, A. Benigni, A. Helmedag, K. Chen, D. Cali, P. Jahangiri, D. Muller, and A. Monti, "Multiphysics test bed for renewable energy systems in smart homes," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 1235–1248, Mar. 2013.
[41] S. Raman, N. Sivashankar, W. Milam, W. Stuart, and S. Nabi, "Design and implementation of HIL simulators for powertrain control system software development," in *Proc. Amer. Control Conf.*, 1999, pp. 709–713.
[42] M. Steurer, C. Edrington, M. Sloderbeck, W. Ren, and J. Langston, "A megawatt-scale power hardware-in-the-loop simulation setup for motor drives," *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1254–1260, Apr. 2010.
[43] J. Kramer and J. Magee, "Dynamic configuration for distributed systems," *IEEE Trans. Software Eng.*, vol. SE-11, no. 4, pp. 424–436, Apr. 1985.
[44] Y. Xu *et al.*, "A reconfigurable concurrent function block model and its implementation in real-time Java," *J. Integr. Comput.-Aided Eng.*, vol. 9, pp. 263–279, 2002.
[45] L. Wills, S. Kannan, S. Sander, M. Guler, B. Heck, J. Prasad, D. Schrage, and G. Vachtsevanos, "An open platform for reconfigurable control," *IEEE Control Syst.*, vol. 21, no. 3, pp. 49–64, 2001.
[46] D. Villa, C. Martin, F. Villanueva, F. Moya, and J. Lopez, "A dynamically reconfigurable architecture for smart grids," *IEEE Trans. Consumer Electron.*, vol. 57, no. 2, pp. 411–419, May 2011.
[47] V. Calderaro, A. Piccolo, and P. Siano, "Maximizing DG penetration in distribution networks by means of GA based reconfiguration," in *Proc. IEEE Int. Conf. Future Power Syst.*, 2005, pp. 1–6.
[48] D. Shirmohammadi and H. Hong, "Reconfiguration of electric distribution networks for resistive line losses reduction," *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1492–1498, Apr. 1989.
[49] "Technical guideline: Generating plants connected to the medium-voltage network," BDEW German Assoc. Energy and Water Industries, 2008.
[50] "Power generation systems connected to the low-voltage distribution network – Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks," VDE Assoc. Electr., Electron. Inf. Technol., Tech. Rep. VDE-AR-N 4105, 2011.
[51] "General conditions for a temporary arrangement for the frequency-dependent active power control of PV systems in the LV distribution network)," VDE Assoc. Electr, Electron. & Inf. Technol., 2011.
[52] J. Jorgensen, S. Sorensen, K. Behnke, and P. Eriksen, "EcoGrid EU — A prototype for European Smart Grids," in *Proc. IEEE Power Energy Soc. Gen. Meet.,*, 2011, pp. 1–7.
[53] G. Cengic and K. Akesson, "On formal analysis of IEC 61499 applications, Part A: Modeling," *IEEE Trans. Ind. Inf.*, vol. 6, no. 2, pp. 136–144, May 2010.
[54] C. Sünder and V. Vyatkin, "Functional and temporal formal modelling of embedded controllers for intelligent mechatronic systems," *Int. J. Mechatron. Manufacturing Syst.*, vol. 2, no. 1, pp. 215–235, 2009.
[55] T. Strasser, M. Rooker, G. Ebenhofer, A. Zoitl, C. Sunder, A. Valentini, and A. Martel, "Framework for distributed industrial automation and control (4DIAC)," in *Proc. IEEE Conf. Ind. Inf.*, 2008, pp. 283–288.
[56] R. Teodorescu, M. Liserre, and P. Rodríguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Hoboken, NJ, USA: Wiley, 2011.
[57] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," *IEEE Trans. Power Electron.,*, vol. 22, no. 4, pp. 1107–1115, Apr. 2007.
[58] K. Dyke, N. Schofield, and M. Barnes, "The impact of transport electrification on electrical networks," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3917–3926, Dec. 2010.
[59] *Voltage Characteristics of Electricity Supplied by Public Electricity Networks*, Project Nr. 22961, European Committee for Electrotechnical Standardization (CENELEC) Std. EN 50160, 2010, .

Thomas Strasser (M'09–SM'13) received the Ph.D. degree in mechanical engineering from the Vienna University of Technology, Vienna, Austria.

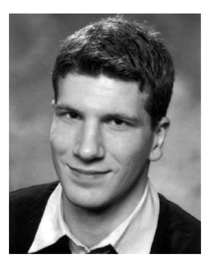
He is a Senior Scientist with the AIT Austrian Institute of Technology, Vienna, Austria, where he is involved with the domain of smart grids with special focus on power utility automation and real-time systems. For more than six years, he has been a Senior Researcher with PROFACTOR research in the field of reconfigurable automation for intelligent manufacturing systems. He coordinated various national and international projects in the domain of intelligent automation and control systems and he is a member of the IEC SC65B/WG15 maintaining the IEC 61499 standard.

Prof. Strasser is member of the IEEE Industrial Electronics Society, the IEEE Systems, Man, and Cybernetics Society, and the IEEE Power Electron Society. He is actively involved in the technical committees IES TC-IA, IES TC-SG, IES Standards-TC, SMCS TC-DIS, and the PES Task Forces on Open Source Software and Real-Time Simulation for power systems.



Filip Andrén (M'12) received the M.S. degree in applied physics and electrical engineering from Linkoeping University, Linkoeping, Sweden, in 2009 .

Since 2009, he has been a Scientist with the Energy Department, AIT Austrian Institute of Technology, Vienna Austria, where he specializes in smart grids and is working with power hardware in the loop as well as control and communication standards.



Felix Lehfuss received the M.S. degree in equipment engineering from the Carinthia University of Applied Science, Villach Austria, in 2010.

He is currently a Junior Engineer with the AIT Austrian Institute of Technology, Vienna, Austria, where he is involved with the field of electric energy systems. His research interests include mechatronics, electrical systems design, control systems, and simulation technologies, especially real-time simulation.

Matthias Stifter (M'09) received the degree in technical cybernetics from Vienna University of Technology, Vienna, Austria.

From 2003 to 2007, he was with the Institute of Computer Graphics and Algorithms, Technical University of Vienna and the University of Technology, Graz, Austria. Since 2007, he has been with the Energy Department, AIT Austrian Institute of Technology, Vienna, Austria. His research interests include distributed generation, active distribution network planning, energy management, and standards for communication and control in smart electricity networks. Since 2008, he has been a national expert for the IEA DSM Task XVII – Integration of DSM, DG, RES and Energy Storages.

Peter Palensky (M'03–SM'05) received the Ph.D. degree in distributed artificial intelligence for demand-side management from the Vienna University of Technology, Vienna, Austria.

He is currently a Principal Scientist with the Energy Department, Austrian Institute of Technology. Before that, he was head of the Business Unit for Sustainable Building Technologies at the AIT, CTO of Envidatec Corporation, Hamburg, Germany, associate professor with the University of Pretoria, South Africa, Department of Electrical, Electronic and Computer Engineering, University Assistant, Vienna University of Technology, Vienna, Austria, and a Researcher with the Lawrence Berkeley National Laboratory. He is active in international committees like ISO, IEEE and CEN. His main research fields are complex energy systems and smart buildings.

Prof. Palensky is an elected AdCom Member of the IEEE Industrial Electronics Society.