Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 44, No. 3 (2014), 185 – 200

Development of Testing Method for Smart Substations with Prosumers

Tarmo Korõtko[1], Ülo Merisalu[1], Marek Mägi[2], Kristjan Peterson[1], Elmo Pettai[1]

[1]Department of Electrical Engineering, Tallinn University of Technology, Tallinn, Estonia
[2]AS Harju Elekter Elektrotehnika, Keila, Estonia

Abstract: The paper presents a concept of design and realization of a new testing method for distribution substations which form a microgrid with prosumers. The distribution substation acts as a service provider for distributed resource units in a microgrid and can be used for bidirectional energy exchange between prosumers, such as electric vehicles, battery pack energy storage devices and utility networks. Use of distribution substations equipped with energy storing and bidirectional energy exchange capability enable peak load shaving and demand response, which will reduce the need for new investments into building new power sources or electric power grids to meet peak demand. While the state of the art in the field analyses mainly different theoretical microgrid topologies and integration of unidirectional distributed energy resources, focus in this paper is on practical issues regarding bidirectional energy exchange, which can provide solutions to microgrid manufacturing enterprises. Protection and control functions of the low voltage part of the distribution substation must be tested prior to exploitation. The new testing method for substations includes both computer simulations and practical verifications for automated energy exchange. Simulation results can be used to define and optimize parameters for protection and control functions before constructing a real microgrid. Functions of an experimental microgrid application were simulated with MATLAB, which showed that several prosumers can be served simultaneously and effectively utilized for peak shaving of utility network loads. The results of the simulations were used to develop sample control algorithms and program modules for the substation controller of the experimental microgrid prototype.

Keywords: bidirectional power flow, electric vehicles, microgrids, smart substation, substation testing methods

Razvoj testnih metod za pametne postaje s proizvajalci-porabniki

Izvleček: Članek predstavlja koncept načrtovanja in realizacije novih testnih metod za distribucijske postaje, ki oblikujejo mikro omrežje s proizvajalci-porabniki. Distribucijske postaje nastopajo kot ponudniki storitve za distribuirane enote virov v mikro omrežju in so lahko uporabljene za dvosmerni pretok energije med proizvajalci-porabniki, kot so električna vozila, hranilne enote in omrežja. Uporaba distribucijskih postaj s hranilniki energije omogoča rezanje vrhov porabe in odzivnost porabe, kar zmanjšuje potrebo po novih investicijah v nove proizvodne kapacitete, ki bi pokrivale vrhno porabo. Medtem ko se trenutne analize osredotočajo na različna teoretična mikro omrežja z enosmernim pretokom energije, ta članek opisuje praktične vidike dvosmernega pretoka energije in nudi rešitve proizvajalcem mikro omrežij. Pred uporabo distribucijskih postaj je potrebno testirati zaščite in kontrolne funkcije. Nove testne metode vključujejo računalniške simulacije in praktična preverjanja avtomatiziranega prenosa energije. Simulacijski rezultati so lahko uporabljeni za načrtovanje in optimizacijo zaščit in kontrolnih funkcij realnih mikro omrežij. Funkcije poskusnega omrežja so bile simulirane v MATLABu. Rezultati so pokazali, da se lahko oskrbuje več proizvajalcev-porabnikov hkrati, ki učinkovito omogočajo rezanje vrhov porabe energije. Rezultati so bili uporabljeni za razvoj kontrolnih algoritmov in programskih modulov za kontrolo postaj prototipnega mikro omrežja.

Ključne besede: dvosmerni pretok energije, električna vozila, mikro omrežja, pametne postaje, testne metode

---

* *Corresponding Author's e-mail: elmo.pettai@ttu.ee*

1 Introduction

Smart Grids and microgrids have attracted much attention due to the increasing awareness of energy conservation and environmental problems. Use of different prosumers (e.g. modern electric vehicles) and their effective integration into electric power grids depends on the technologies applied around distribution substations. The concept of a prosumer has two common meanings: a union of words of a producer with a consumer or a professional consumer [1]. “Producing consumer” type of a prosumer either generates energy or consumes energy. A “professional consumer” is a well-educated, skilled consumer who commonly makes smart purchasing or selling decisions using additional information [1], [2]. Integration of prosumers to electric power grids is beneficial both to utility networks and prosumers. Prosumers can consume or generate electric energy and improve reliability of electric power supply (e.g. peak shaving, frequency regulation, voltage sags) by integrating renewable energy resources to electric power grids more efficiently. Prosumers can earn additional money with selling ancillary services to utility networks.

In energy trading, the role of distribution substations will increase when different types of prosumers are connected to their output bays. In this paper, mainly electric vehicles (EV) with Li-Ion batteries or battery energy storage unit (BESU) applications are considered as prosumers. EVs with vehicle-to-grid (V2G) capability can be charged or discharged through substations. Other types of prosumers that could be connected with distribution substations are generators (e.g. photovoltaic), energy storage units (e.g. supercapacitors, electrolyser, flywheel) or different subsystems (e.g. other bidirectional distribution substations, microgrids or smart homes).

The aim of this paper is to develop a new testing method for the next generation distribution substations (smart substations), which includes optimization of requirement validation algorithms and testing scenarios (defined according to the rules of testing functions), and selecting proper parameter values for protection and control functions. The method can be applied in the construction of new distribution substations (existing substations are typically designed for given purpose and do not have reserve space to expand to include energy storage).

The developed method will be used in the construction of an experimental microgrid prototype. For transparency, example control topologies for the substation controller are presented.

The paper is divided into ten main parts. Parts 2 and 3 describe the state of the art of smart substations and the proposed topology for smart distribution substation. Part 4 describes the state of the art of substation testing methodology. Part 5 introduces the new approach to substation development methodology. The substation organization and control architecture are firstly described and simulated according to the requirements, then saved for reuse in a repository. The results are practically verified during the experiments, using the experimental microgrid, and production cycle of the smart substation, and finally accepted by prosumers. General functional requirements and parameters are defined for distribution substations with prosumers (BESU and EV). Part 6 discusses the principles of the development and testing of control algorithms for the central controller of the distribution substation. Part 7 describes simulation of the control functions for bidirectional energy exchange between Li-Ion prosumers and the utility network with MATLAB Simulink. Parts eight and nine discuss the principles of testing novel distribution substations and the data required during the tests from prosumers. Finally, future studies and conclusions are presented.

2 State of the art of smart substations

Several papers have addressed microgrid (distributed resource island systems according to IEEE 1547.4) architectures [3]-[8], V2G architectures [9], [10] and bidirectional converter topologies [11], [12]. However, research papers regarding testing of microgrids or presenting technical analysis about control functions for automated bidirectional energy exchange between distribution substations and several prosumers are scarce. Several papers have addressed the concept of virtual power plants (VPP) [13], [14], but no technical analyses show how the concept could be realized in real applications.

Some reports address the testing of distributed resource units [15], PV [16] or V2G [17] applications and energy storage systems [18], [19], but not regarding prosumers in general.

Some companies are using the term “smart substation” [20] to describe substations, which only monitor and transmit data to a microcontroller or outside server. These types of substations include no devices e.g. for suppressing harmonics [21] or providing uninterruptible power supply.

Today’s smart substations are either in the planning or in the prototype phase. Few projects can be found in field testing [22], [23].

It can be concluded that distribution substations for integrating prosumers to electric power grids are still in the development phase. IEEE 1547 standard presents mandatory requirements [24] for interconnection itself and testing. IEEE 1547 standard is not a design handbook or application guide. Thus, it is necessary to solve how to construct next generation distribution substations and how to test these substations.

3 Topology of distribution substation for integrating prosumers with utility network

Transformer substations are part of the electric power system concentrated in a given place to transmit electric energy, distribute power and step up or down the voltage. Substations for medium voltage grids (typically 6-24 kV) transform 3-phase medium voltage to 3-phase AC low voltage (typically 400 V AC).

State of the art distribution substations do not include bi-directional energy exchange capability between prosumers, LV side consumers and utility network. Next generation distribution substations could control electric power quality in a local area, maximize benefits for prosumers and owners of microgrids, integrate several prosumers to electric power grids (e.g. large EV parking lots).

An example of a distribution substation topology for microgrids is presented in Fig. 1.

The substation consists of a MV switchgear, a transformer and a low voltage (LV) switchgear (with switches, smart meters, contactors and power converters). The substation allows bidirectional energy exchange between all the prosumers and consumers that are connected with the integrated AC & DC bus, and transfer energy to the utility network. Prosumers are connected either to behind AC/DC power converter with a common DC bus or to a common AC bus. For every prosumer in the common DC bus separate protection and switching apparatuses are available at the DC side.

The BESU in the substation is connected with the common DC bus. The DC bus voltage can float in the specified voltage range to increase the efficiency of energy conversion. For example, the BESU can support fast charging of EVs, provide backup energy and power capability for a utility network power outage. As the number of renewable energy sources is increasing in the grid (e.g. wind and solar energy), the balancing of excess generation sources and load demands can be controlled through the substation. This enables stabilization of the grid AC voltage and frequency [23].

The presented distribution substation topology is beneficial mainly to the future owners of a microgrid (e.g. manufacturing enterprises) for controlling energy storage and usage inside the microgrid. The master controller of the substation can be adjusted (e.g. scheduling, trading, optimization) according to the needs of the future owners of the microgrid.

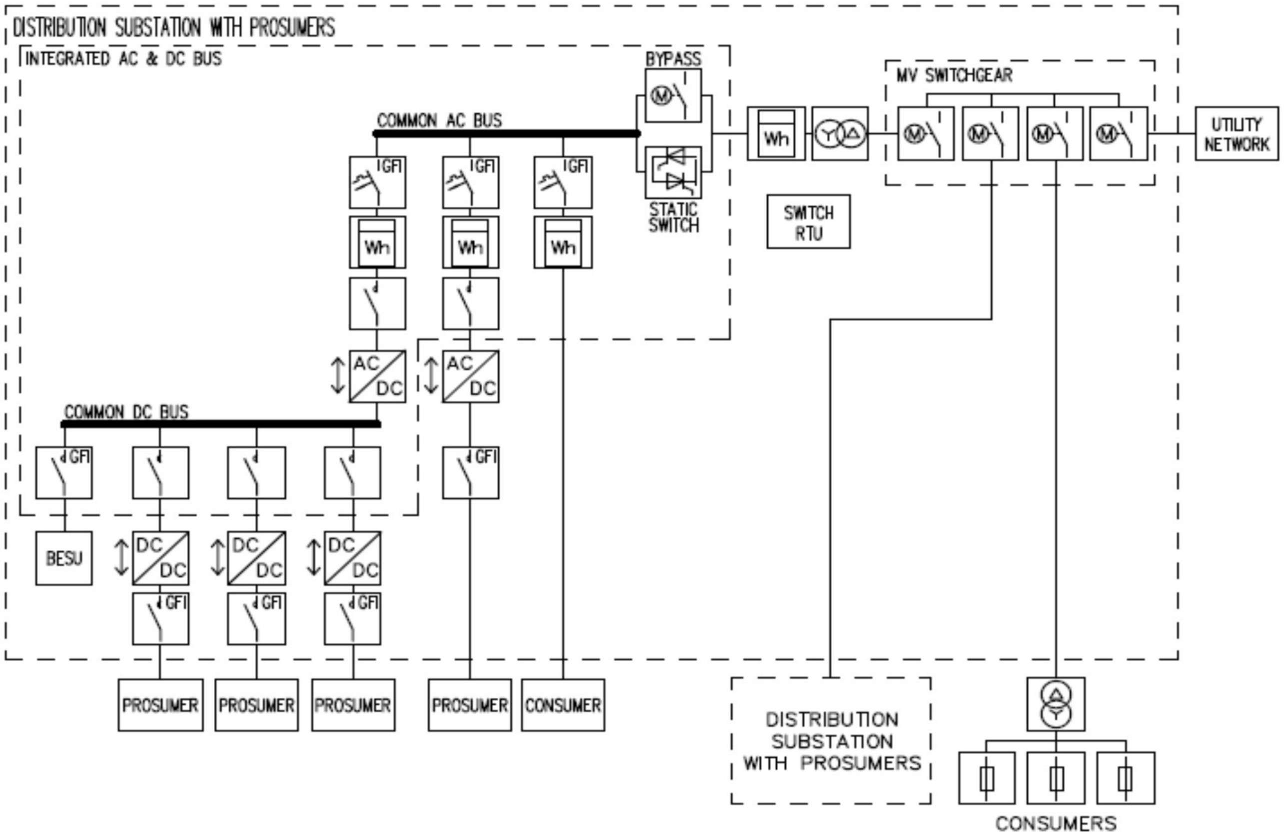


Figure 1: Topology of a distribution substation with an integrated AC & DC bus and prosumers for microgrid applications.

4 State of the art of substation testing methodology

Ordinary substation testing is divided into factory routine tests and field tests [25]. Factory routine tests are divided into visual tests, mechanical tests and electrical tests.

During visual factory tests, a general check is carried out to ensure the hardware is in accordance with project documentation, there exist no errors of assembly and all labels are correct. Also the absence of leakages will be checked.

The tightness of all electrical and mechanical connections will be checked during factory tests.

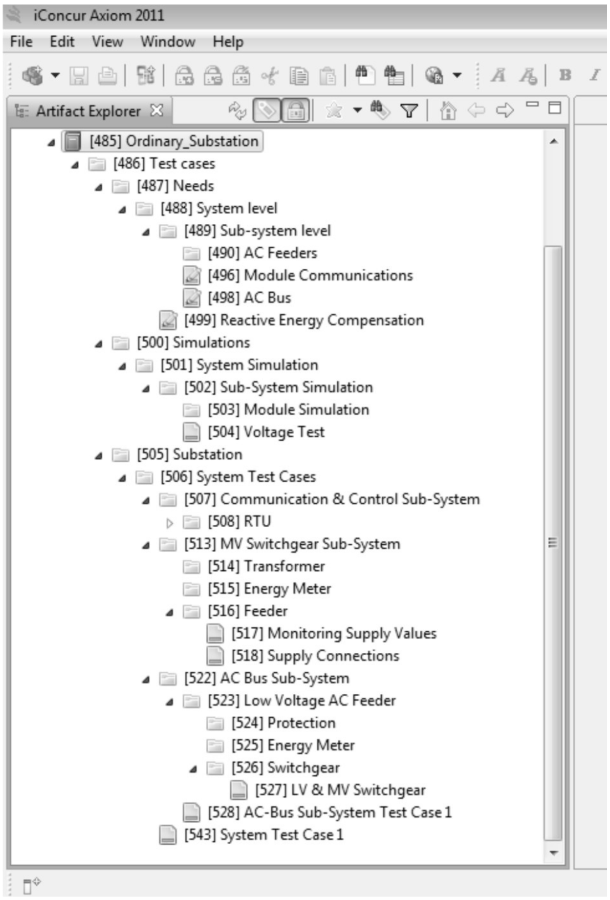
Electrical factory tests include: installation correctness (topology), wire insulation resistance and tests of protection and switching apparatus. Transformer parameters will also be checked [25]. A very important part is to test the substation under nominal current and voltage (separately).-

Substation field tests are is similar to factory tests. During mechanical field tests, only the connections installed on site will be tested. Electrical field tests measure the insulation resistance of only those cables which are installed on site. Protection systems and switchgear will also be tested on site. The testing methodology details will vary in different countries and legislative areas. [26], [25], [27].

The information structure (testing requirements, testing methods, test cases, functional descriptions and other detailed views as source texts of control programs) of an ordinary substation can be represented using a requirements definition software e.g. Axiom (Fig. 2).. The collected information is used as reference during optimization, validation, and verification processes.

The software allows parallel use of requirements information, simulation and verification data enable faster validation of microgrid projects.

Independent certification of specified and tested microgrid modules, such as energy storage systems, can reduce installation time at customer site from weeks to hours, since certification transforms energy storage from a nascent technology into a safe plug-and-play appliance. After the integration of the system (substation, prosumers and utility), main use cases need to be tested. The verification process commonly demands rigorous testing and evaluation and is a time consuming and costly process.



- [485] Ordinary_Substation
  - [486] Test cases
    - [487] Needs
      - [488] System level
        - [489] Sub-system level
          - [490] AC Feeders
          - [496] Module Communications
          - [498] AC Bus
        - [499] Reactive Energy Compensation
    - [500] Simulations
      - [501] System Simulation
        - [502] Sub-System Simulation
          - [503] Module Simulation
          - [504] Voltage Test
    - [505] Substation
      - [506] System Test Cases
        - [507] Communication & Control Sub-System
          - [508] RTU
        - [513] MV Switchgear Sub-System
          - [514] Transformer
          - [515] Energy Meter
          - [516] Feeder
            - [517] Monitoring Supply Values
            - [518] Supply Connections
        - [522] AC Bus Sub-System
          - [523] Low Voltage AC Feeder
            - [524] Protection
            - [525] Energy Meter
            - [526] Switchgear
              - [527] LV & MV Switchgear
          - [528] AC-Bus Sub-System Test Case 1
        - [543] System Test Case 1

Figure 2: Screenshot of testing requirements for ordinary distribution substation.

5 New approach to substation development methodology

The substation testing methods, which were described in the previous part of this paper, are included in the construction of a new methodology. The new methodology is based on a software development methodology (X-model) and is visually represented in Fig. 3. During software testing, it is useful also to follow IEEE standard 829-2008 recommendations. The Requirements box (including e.g. application software functional requirements, substation user requirements, use cases etc.) is visualized in the left-upper part of Fig. 3. Documentation and repositoring is visualized in the left-lower part of Fig. 3. Prototype construction is visualized in the right-lower part of Fig. 3. Producing is visualized in the right-upper part of Fig. 3.

Next chapters of the paper introduce some control aspects of the smart substation and their testing methods.

Functional requirements and parameters for distribution substations with prosumers are described in different standards (e.g. IEEE 1547.1 and VDE-AR-N 4105 [28]).

IEEE 1547.1 standard describes test procedures for equipment interconnecting distributed resources (e.g. prosumers) with electric power systems. In addition, the German standard VDE-AR-N 4105 provides for the improved network integration of decentralized power generation (in particular, inverter-based generators).

During normal operation, the magnitude of the voltage change caused by the generating prosumers must in any connection point not exceed a value of 3 % compared to the voltage, when the generating prosumers were not connected. Voltage change of 3 % in the connection or disconnection with the distribution substation should not occur more frequently than once every 10 minutes.

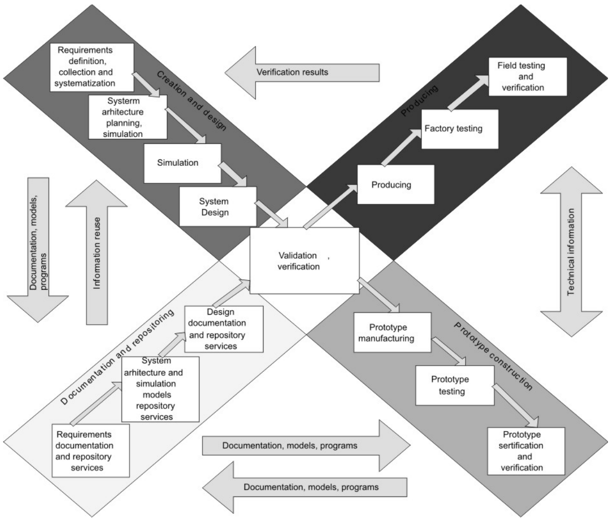


Figure 3: Substation testing methods in the developed methodology.

VDE-AR-N 4105 specifies the disconnection of inverters connected to the LV network due to grid side disturbances [29]. When the voltage variation (undervoltage, overvoltage) exceeds the limits $80\%U_n<U_{pcc}<110\%U_n$, disconnection is necessary within 100 ms. In case the upper limit is exceeded, according to EN 50160, inverters must shut down. If the frequency limits $47.5Hz<f_n<51.5Hz$ are exceeded, the inverters must disconnect in 100 ms. The inverters are allowed to reconnect after a fault, when the following conditions are satisfied: $85\%U_n<U_{pcc}<110\%U_n$, $47.5Hz<f<50.05Hz$, minimum delay of 5 s. The specific behaviour of the inverters and controlled rectifiers under a grid faults is very important, since it is desired that the system avoids disconnection as much as possible.

Frequency variation is a common problem which affects power systems. To avoid unbalanced conditions, distribution substations serving prosumers must be capable of adjusting power production by means of frequency regulation. Generating substations with the capacity over 100 kW have to reduce their real power in steps of at most 10 % of the max. active power [29]. Generating bays have to reduce their power output with a gradient of 40 % Hz, when a 50.2 Hz frequency limit is surpassed. The output power is allowed to increase again when the frequency is below 50.05 Hz. Outside the frequency limits, the bays have to disconnect from the grid. Controllable substations have to reduce the power output to the target value within a maximum period of time of 1 minute. If the set point is not reached in the mentioned time period, the generating prosumers must be disconnected.

6 Testing of control algorithms for the central controller of the distribution substation

The Remote Terminal Unit (RTU) acts as a central controller in the substation and also as the master in a microgrid. Each prosumer might include its own control unit handled as a slave device that serves the purpose of controlling prosumer related lower level tasks. The RTU operates the substation in general, while the functionality of safe and fast fault response is handled by protection apparatus (fuses, circuit breakers etc.). The purpose of the powerful RTU is to read the status and operational parameters of microgrid prosumers, to send control values and configuration information to the slave devices, to control bidirectional energy exchange between prosumers and the utility network (control of prosumer and utility bays), and to perform the following functions: scheduling, electricity trading (with electricity retailer), grid constraints observer (retrieve information from distribution system operator) and interface provider to EV owners (e.g. departure time, energy prices). In regard to the topology (e.g. integrated AC & DC bus) chosen, each bay for a prosumer might include its own slave controller or the central RTU could control all prosumer bays itself.

Communication between intelligent electronic devices (IEDs) of the next generation substation, including RTU and prosumers, should be realized with the IEC 61850 protocol [1] as much as applicable. The IEC 61850 protocol uses Ethernet as the basic communication technology, currently at a speed of 100 MBit/s. Different protection and control functions should be scattered between substation devices in order to speed up data flow between the devices [30].

Control algorithms for the RTU have to be tested prior to the exploitation of the distribution substations. This requires verification of the protection and control algorithms both in the simulation and laboratory environment, and then in factory testing.

Before any energy exchange in either direction can be executed, the communication side must be tested with data retrieval and sending. If the communication link is available and safe, data is being polled by RTU from the prosumer. For example, for EVs it is required to monitor the battery current and temperature in order to protect the prosumer during charge and discharge, thus it is necessary to gather the following data about the battery of the prosumer: state of charge (SOC), state of health (SOH), battery pack open circuit voltage, measured temperature values and nominal values of various BMS predefined parameters (rated capacity, maximum and minimum values of battery pack voltage, SOC levels, current and temperature).

To provide the best service to the prosumer (e.g. owner of the EV), the RTU needs data about the maximum possible time period the prosumer could stay connected to the microgrid, minimum SOC level required before departure and an agreement from the prosumer to allow partial discharge of the battery, which would be compensated according to the agreement with the service provider. This information can either be received remotely by the RTU or partially entered using a user interface (human to machine interface (HMI) panel, smartphone application etc.).

After testing the communication, protection functions have to be tested in order to evaluate and determine whether it is safe to proceed or not. This requires the presence of the main supply for testing. The algorithm for the RTU contains many protective functions:

- AC side protection functions are mainly realized by intelligent bay controllers (e.g. modern smart meters), ensuring that voltage and frequency are in the determined range and current values do not exceed defined maximum values. Digital input data from smart meters for the RTU:
  - automatic or manual mode of charge,
  - AC side circuit breaker closed,
  - positions of AC side contactors,
  - positions of the isolation monitoring devices
  - power related quantity values,
  - faults.
- DC side protection functions realized by the RTU for each bay ensure that DC side primary and auxiliary voltage values are in the determined range, current values do not exceed maximum values. Digital input data:
  - positions of DC side circuit breakers and contactors,
  - positions of isolation monitoring devices,
  - EV connector locking.
- General protection functions realized by the RTU ensure that parameter values of prosumers' BMSs and power converters are in the determined range, active monitoring of AC and DC side protection inputs, emergency stop pushbuttons not activated, connection termination not required by EV owners.

It must be verified that all data is being collected and logged by the RTU in order to generate operation and error reports.

If any of the criteria set by the protection functions is not met, the charge or discharge of prosumers must not be allowed and should be interrupted (soft stop) if a fault occurs during a process. All critical protection functions are carried out redundantly, independent of the RTU, and will be triggered automatically (hard stop) when fault conditions occur.

When the general protection functions have been tested, the RTU processing side can be tested. When no error conditions are present, the RTU must calculate the process values using polled and user defined data. Data used from processing must activate the AC/DC and DC/DC power converters in the predefined sequence and parameters values are to be downloaded to the power converters. Contactors behind DC/DC converters (at DC bus side) allow the switching of DC voltage to prosumers when DC/DC converters are ready in the buck mode. Contactors before DC/DC converters allow the switching of DC voltage to the common DC bus when DC/DC converters are ready in the boost mode. The position and status data of prosumer bay devices are transferred to the RTU for signalling purposes, for example, which substation bays are currently online and exchanging energy with prosumers (offline bays are reported in error reports).

If it has been verified that protection functions and operation of power converters run according to the control algorithm in RTU, predefined control algorithms for the system can be tested. The tests are based on typical use cases.

6.1 Charge

Figure 4 presents an example of an action flow chart for a prosumer charging use case (operation) [31]. Table 1 specifies the abbreviations and parameters used in Figs. 4 and 5. The command for charging is initiated by the prosumer (EV or BESU user). Some EVs need to follow the CHAdeMO protocol [32]. For EVs, the charging start signal is sent to the EV. If protection functions are fulfilled, AC contactors for AC/DC converters positioned in front of the common DC bus are closed. AC/DC converters will receive target output voltages and power values from the RTU and will be set to rectifier mode. DC/DC converters are operating in the buck or boost mode. The DC/DC converters will receive target secondary side output voltage and power values from the RTU. If the common DC bus voltage is in range by the AC/DC converter, contactors on the primary side of the DC/DC converters are closed. When the DC/DC converter output voltage is in range, the BESU's BMS is set to the charge mode. For EVs, the connector is locked and the isolation test is performed, also contactors of the secondary side of DC/DC converters are closed. At the beginning of the charging process the SOC level of prosumers will determine whether the charge is performed with a slow current value, constant maximum current value or with constant voltage. The choice of the charging mode will be adjusted in accordance with the battery SOC value. For EVs charging is stopped at the zero current signals or timeout from the EV side. Depending on the location of fault detection, fault events will immediately open the adjacent switching apparatus.

6.2 Discharge

Figure 5 presents an example of an action flow chart for a discharging use case (operation) [31]. The command for discharge initiates the function for the selection of a prosumer type (EV or BESU user). For EVs the connector is locked and the isolation test performed. Contactors of the secondary side of the DC/DC converters are closed, the DC/DC converters receive a target for the primary side output voltage and power values from the RTU. When the output voltages of DC/DC converters are in range, the contactors of the primary side of the DC/DC converter are closed. Active power is transferred to the common DC bus. AC contactors for AC/DC converters (that are installed before the common DC bus) are closed if energy flow is directed from DC bus to AC bus side.

AC/DC converters will be set to the inverter mode and the RTU determines the target output power value for the AC/DC converter. The AC/DC converter synchronizes with the common AC bus voltage and power is transferred to the common AC bus. The time of discharge of prosumers (EV, BESU) depends on the quantity of resources acquired from the substation to perform its service providing. Discharging of prosumers is stopped when the depth of discharge, maximum discharge current or temperature is exceeded or the SOC value drops below the value defined in the manufacturer specifications [33]. Switching apparatuses are opened and operation of power converters stopped according to the determined sequences (determined stop or fault detection).

Table 1: Abbreviations and parameters in figs. 4 and 5

START	program cycle start
Check. Comm	communication check function
Status.Comm	communication status data object
Status.Comm.Err	communication error status
Poll	function to poll data from the prosumer
Data	RTU internal database for process values
Protection	function for carrying out protection functions
Calculate Process Values	function for calculating process values
Data.Prot.AC_B_err	AC bus error data object
Data.Prot.DC_B_err	DC bus error data object
Data.Pros.Chrg	prosumer charge command data object
Data.Pros.DsChrg	prosumer discharge command data object
Wake BESU	BESU wakeup function
Sleeping P-conv. to stand-by	function for setting power converters currently in sleep mode to stand-by
Close AC contactor	AC contactor closing function
Write process data to conv.	function for writing process data to converters
Write DC/DC conv. val	function for writing DC/DC converter process values
Write AC/DC conv. val	function for writing AC/DC converter process values
Set AC/DC conv. To Rectifier m.	function for setting the AC/DC converter to operate in the rectifier mode
Set AC/DC conv. to Inverter m.	function for setting the AC/DC converter to operate in the inverter mode
Set DC/DC conv. to Buck m.	function for setting the DC/DC converter to operate in the buck mode
Set DC/DC conv. Boost m.	function for setting the DC/DC converter to operate in the boost mode
Data.Pros.DC_PBus_U_OK	DC prosumer primary bus voltage status data object
Close DC/DC conv. prim. Cont.	function for closing the DC/DC converter primary side contactor

Data.Pros.DC_SBus_U_OK	DC prosumer secondary bus voltage status data object
Data.Pros.DC/DC_Rdy	prosumers DC/DC converter ready state status data object
Data.Pros.Cap_DisCh	prosumers DC/DC converters capacitors need for discharge status data object
Data.Proc.Synch_OK	AC/DC converter AC output in synchronization with the AC bus status data object
Close DC/DC conv. sec. cont.	function for closing the secondary contactor of the DC/DC converter
Open DC/DC contactors	function for opening the primary and secondary contactors of the DC/DC converter
D.chrg DC/DC conv. cap	function for discharging the DC/DC converter capacitors
Close AC/DC Conv. AC cont.	function for closing the AC contactor of the AC/DC converter
END	end of program cycle

7 Simulation of bidirectional energy exchange between prosumers and utility network

Before microgrid system integration tests, (typical) use cases are to be simulated (visualized in left part of Fig. 3). This is done before prototype, factory and field tests, which are carried out using real hardware (visualized in right part of Fig. 3). Computer simulations provide a first testing environment for different control algorithms, allow optimization of energetic parameter values and a selection of devices for protection and control functions. Figure 1 shows a distribution substation topology that is similar to the topology simulated using the MATLAB Simulink model (Fig. 6) [31]. The model consists of 24 kV utility network supply through an MV switchgear, a 250 kVA voltage transformer 24/0.4 kV and an LV switchgear, which interconnects consumers and prosumers. The LV switchgear is divided into a common AC bus and a common DC bus. In this paper the BESU, (including Li-Ion battery pack with the nominal voltage of 460 V DC) is considered as prosumer in the MATLAB Simulink model. Other prosumers are connected with the common DC bus through bidirectional DC/DC power converters DCDC1-DCDC3 (double-leg full bridge DC/DC power converter topology with galvanic isolation). Contactors are included in the bays before and after the bidirectional DC/DC power converters. The common DC bus is supplied through a 100 kVA bidirectional AC/DC power converter ACDC1 (three-level neutral point clamped voltage sourced converter). The common DC bus voltage can be adjusted up to 800 V DC. Consumers consuming 100 kVA to 200 kVA are connected with the common AC bus.

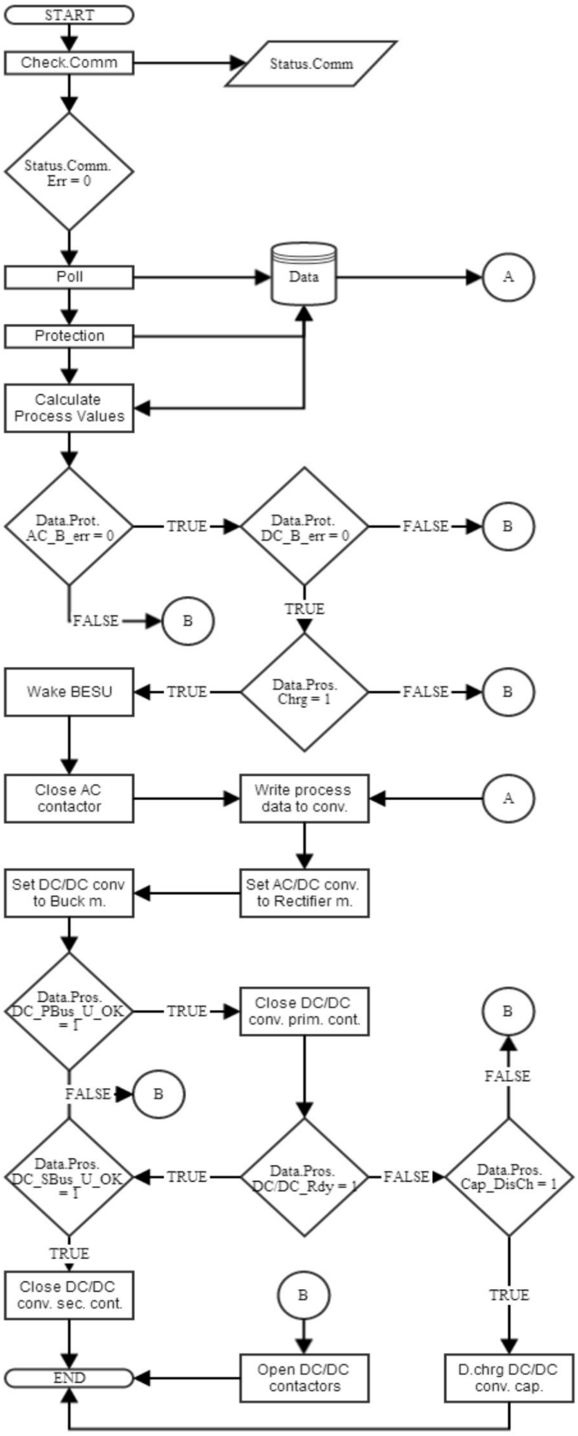


Figure 4: Action flow chart for the prosumer charging operation.

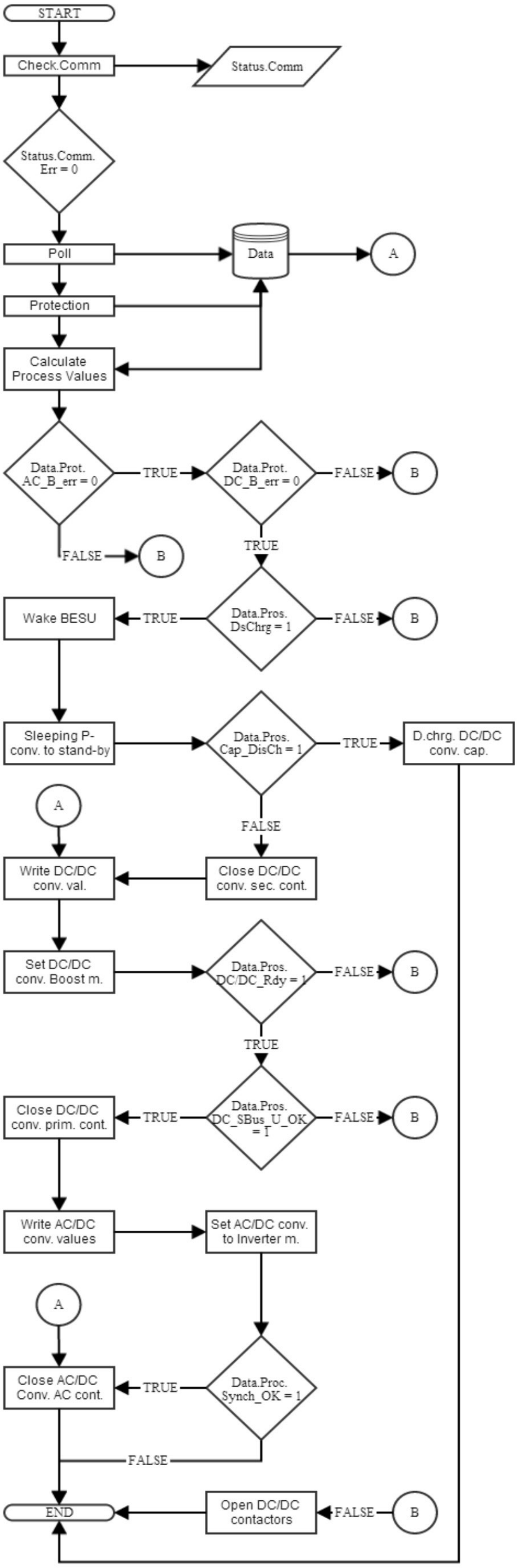


Figure 5: Action flow chart for the prosumer discharging operation.

The purpose of the MATLAB Simulink model is not to simulate a particular bidirectional AC/DC or DC/DC power converter, but rather to evaluate control functions (scripts) for bidirectional energy exchange and power distribution between the prosumers and the utility network. The simulated, tested (using the experimental prototype in laboratory) and verified control algorithms describing the control functions will be downloaded to a substation controller during the production of such a smart substation.

Some important systems integration tests can be carried out out much faster if user requirements, data models (systematized by developers) and the data values collected during simulations, laboratory experiments and factory tests are available also during site tests. Parallel recording and using the requirement information, simulation and verification data enable faster validation and approval of a microgrid project.

Independent certification (described in part 4 and visualized in lower right part in Fig. 3) can significantly reduce installation time spent at customer site.

During simulations, firstly, the consumer stage of a single prosumer (PROSUMER1) is examined. The bidirectional AC/DC converter ACDC1 operates in the rectifier mode and supplies the common DC bus.

The bidirectional DC/DC power converter DCDC1 in the prosumer bay operates in the buck mode. The results from the simulated model are presented in [31]. The charging current is ramped up smoothly and maintained at constant current level with the rising of the internal voltage of the Li-Ion battery pack.

Secondly, the producer stage of prosumers is examined. All three prosumers (PROSUMER1-PROSUMER3) provide support to the common DC bus. The support is utilized, for example for the peak shaving of the 200 kW load of the consumers for the utility network. The target goal is to reduce the load of the consumers for the utility network to 100 kW. The bidirectional DC/DC power converters DCDC1-DCDC3 operate in parallel in boost mode. The bidirectional AC/DC power converter ACDC1 operates in inverter mode and supplies the common AC bus. The results from the simulated model are presented in [31].

The simulations also help to define value ranges of resistances of possible electrical circuits. Internal resistance R_i of generating/consuming prosumers can be calculated and later tested from the voltage drop/rise ΔU during energy exchange with a constant current I. Designed BESU energy density can be predetermined by simulations. Effective gravimetrical energy density

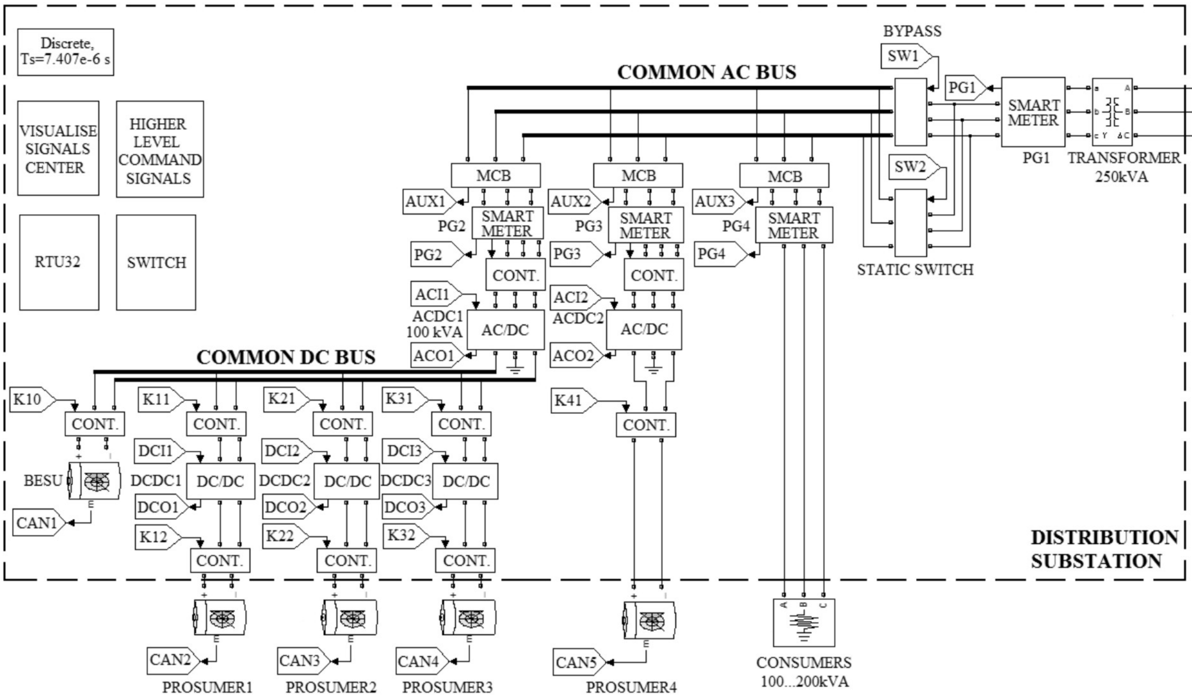


Figure 6: MATLAB Simulink model of a distribution substation with prosumers.

of modern lithium-ion batteries is about 100 to 265 Wh/kg.

Power density or the time rate of energy transfer is either measured gravimetrically (kW/kg) or volumetrically in kilowatt per litre (kW/l). Power density combines the energy density with the speed at which the energy can be delivered from one prosumer to the other or can be absorbed by a load. The actual speed is characterized by electric current.

The maximum power of an electric circuit is given by the formula $P_{max} = U^2/R_i$, where U is voltage applied and R_i, is the internal resistance of the circuit. The P_{max} specifies the power of a rectangular single maximum current peak of a given voltage. In reality the current peak is not rectangular caused by time constants and the voltage change is caused by the voltage drop. For supercapacitors the IEC 62391–2 standard therefore proposes a formula to calculate a more reality oriented effective power P_{eff} for power applications:

$$P_{eff} = \frac{1}{8} \times \frac{U^2}{R_i} \tag{1}$$

8 Test method for smart substations

Protection and control functions of smart substations have to be tested prior to exploitation. This includes running computer simulations, factory testing and onsite tests. Table 2 presents an example testing protocol for distribution substations that includes BESU and providing services for prosumers. For factory testing of the substation a variable voltage and frequency supply unit, load simulator and a test prosumers (e.g. EV and emulated PV plant that is based on programmable DC source) are required.

The testing method sequence begins with general routine tests for LV & MV switchgears, RTU and distribution substation. Settings and parameters need to be downloaded to devices and HMI.

Computer simulations verify the designed control algorithms and provide dynamic values (e.g. voltage and current values), which can be used for adjusting settings for protection and control devices. Differences between simplified computer simulations and practical test results should not exceed 10 %.

When the testing has been prepared, test supply unit can be connected and the behaviour of the system monitored.

Before connecting test loads, bays of the distribution substations must be prepared. This requires verification that protection functions run properly. Protection functions should be dependable (will operate when required), secure (will not operate when not required), selective (respond to events within their zones). Bay parameters have to be inserted and control of bays through RTU has to be verified. At the end of the preparation of the bays the operation of power converters has to be tested.

After preparations and supply connection, test loads can be connected. Data retrieval and controllability of the prosumer's local controller (BMS) must be verified. Consumption and production stages (e.g. charging and discharging of the test EV) can be then tested for test prosumers and BESU.

IEEE 1547.1 type (design) tests are included in Table 2. The temperature stability test verifies that interconnection equipment maintains measurement accuracy of parameters over its specified temperature range. Abnormal voltage and frequency test verify that the system ceases to energize the area electric power system (EPS) in abnormal conditions. The synchronization test demonstrates that interconnection equipment will accurately and reliably synchronize to the area EPS. Interconnection integrity tests include verification for protection from electromagnetic interference (EMI), surge withstand performance and dielectric tests on the paralleling device. DC injection test verifies that the system complies with the DC current injection limit. Function tests include means to determine that the system ceases to energize the area EPS in unintentional island condition and loss of phase. Reconnect time test verifies the functionality of the reconnect timer in trip event. Harmonic tests measure individual current harmonics and total demand distortion (TDD).

IEEE 1547.1 production test verifies the operability of every unit of the interconnection equipment manufactured for customer use. Commissioning tests (onsite tests) are conducted after the interconnection system is installed and is ready for operation. Flicker tests are site dependent.

Onsite testing is vital prior to exploitation to verify that all the protection and control functions run properly. Specific functions like peak shaving, frequency droop control, reactive power compensation and intentional islanding can be monitored and test results protocolled. Time response to unintentional islanding should be 2 s according to IEEE 1547 requirement. During onsite testing the remote controllability of the distribution substation for the utility network can be verified. Some functions of the distribution substation have to be monitored over a longer period of time. These functions include ambient temperature tests to verify how much the prosumers and BESU can actually support in the production stage at different ambient temperatures (e.g. in winter and summer periods). The data can be used for accurate forecasting. The operations of data storing and scheduling functions must be verified.

Table 2: Testing protocol for distribution substation

No.	Description of test sequence	Status
	Factory tests	
1.	**Preparation for testing**	
1.1.	Routine tests for LV & MV switchgears and distribution substation	
1.2.	RTU testing (data retrieval, control of outputs)	
1.3.	Computer simulations for protection and control settings	
1.4.	Download of parameters and settings to power converters and smart meters	
1.5.	HMI set-up	
2.	**Connection of test sources and communications**	
2.1.	Supply connection	
2.2.	Monitoring of supply values (e.g. voltage, frequency)	
2.3.	Communication set-up and data flow	
3.	**Preparation of bays**	
3.1.	Protection ensured, interlocking of bays	
3.2.	Nominal, max. and min. values inserted for bays	
3.3.	RTU connection sequences (e.g. operation of contactors)	
3.4.	Activation of AC/DC and DC/DC power converters	
3.5.	Control response and data retrieval of AC/DC and DC/DC power converters	
4.	**Connection of test loads and BESU**	
4.1.	Data retrieval and controllability of prosumer controller (BMS)	
4.2.	Execution of example charging test sequence	
4.3.	Report from charging sequence (protection status, control functions, power quality)	
4.4.	Execution of example discharging test sequence	
4.5.	Report from discharging sequence (protection status, control functions, power quality, voltage rise, time responses)	
4.6.	DC input mismatch wiring test	
4.7.	First full charge of BESU	
4.8.	BESU functions testing (charge, discharge)	
5.	**IEEE 1547.1 type (design) factory tests**	
5.1.	Temperature stability	
5.2.	Responses to abnormal voltage	
5.3.	Responses to abnormal frequency	
5.4.	Synchronization in production stage	

5.5.	Interconnection integrity	
5.6.	DC injection	
5.7.	Unintentional islanding	
5.8.	Ceases to energize functionality and loss of phase (simulated fault sequences, emergency stop sequence)	
5.9.	Reconnect time and sequence	
5.10.	Harmonics	
6.	**Onsite (Field) testing of complete system behaviour**	
6.1.	Download of parameters and settings of the end user to devices	
6.2.	Peak shaving functional test	
6.3.	Frequency droop control in production stages	
6.4.	VAR management (reactive power compensation)	
6.5.	Power conditioning (PQ) and harmonic suppression	
6.6.	Intentional islanding and resynchronization	
6.7.	Power balancing in islanding mode	
6.8.	Blackstart management	
6.9.	Flicker test (site dependent)	
6.10.	Network communications (control from utility network)	
6.11.	Utility network supply accordance to EN 50160	
6.12.	Ventilation verification for heat extraction	
6.13.	Data storage (metering) and access through cloud applications	
6.14.	Scheduling tests	
6.15.	Ambient temperature tests (production stages of the prosumers and BESU)	
7.	**Conclusions**	
7.1.	Compliance with different international standards (EN 50160, IEC 61000, IEEE 1547.1 etc)	
7.2.	Remarks and limitations	
	Verification	

Table 3 presents an example of a generalized test report of the testing protocol for distribution substations. Different parameters have to be monitored and protocolled at consumption stage and production stage of the prosumers and also during different ancillary functions. The measurement values can be divided into three main categories: prosumer side, common DC bus side and utility network side.

Table 3: Test report with measured values

No.	Description of measurements	Value
	Field testing	
1.	**Prosumer DC side and BESU measurements both for consumption and production**	
1.1.	DC side voltage (start, end)	
1.2.	DC side current (max., average)	
1.3.	SOC values (start., end)	
1.4.	Active power (max., average)	
1.5.	Transferred energy (kWh)	
1.6.	Temperature of prosumer elements and DC/DC power converters (max., average)	
1.7.	Efficiency of DC/DC conversion	
1.8.	Specific energy (gravimetric mE, volumetric VE)	
1.9.	Specific power (gravimetric mP, volumetric VP)	
1.10.	Ambient temperature	
1.11.	Duration of full test and cycle times (e.g. constant current, constant voltage). Sampling rates.	
2.	**Common DC bus measurements during consumption or production of energy by prosumers**	
2.1.	Common DC bus voltage (max., min., average)	
2.2.	Common DC bus voltage unbalance (max., min., average)	
	Field testing	
2.3.	Common DC bus current (max., average)	
2.4.	Temperature of AC/DC power converters (max., average)	
2.5.	Efficiency of AC/DC conversion	
2.6.	Active power (max., average)	
2.7.	Transferred energy (kWh)	
3.	**Utility side measurements during consumption or production of energy by prosumers**	
3.1.	AC voltage (max., min., average, unbalance)	
3.2.	AC current (max., average)	
3.3.	AC frequency (max., min., average)	
3.4.	Active power, Reactive power, Apparent power (max., average)	
3.5.	Power factor (max., average)	
3.6.	Transferred energy (kWh)	
3.7.	Harmonic distortion (THDU, THDI, TDDI) with 1 to N activated prosumers at DC or AC side	
3.8.	Voltage flicker	
3.9.	Total efficiency of energy conversions	

3.10.	Duration times to load/production reduction: 25%, 50%, 75%	
3.11.	Inrush max. current and duration	
3.12.	Isolation monitoring and leakage currents	
4.	**Additional utility side measurements during production of energy by prosumers**	
4.1.	Max. continuous output power	
4.2.	DC current injection	
5.	**Functional test reports**	
5.1.	Clearing time to abnormal voltage (<U, >U)	
5.2.	Clearing time to abnormal frequency (<f, >f)	
5.3.	Clearing time unintentional islanding	
5.4.	Clearing time to simulated faults	
5.5.	Duration time for recovery (from abnormal area EPS values to nominal values)	
5.6.	Duration time for recovery (fault trip clearance)	
5.7.	Duration time to intentional islanding	
5.8.	Duration time to resynchronization	
5.9.	Duration time to blackstart	
5.10.	Duration time to peak shaving (target value, duration time and reference signal tracking error)	
5.11.	Ramp rate to active power production	
5.12.	Active power reduction gradient in frequency regulation	
5.13.	Duration time for VAR Management (target value, duration time, reference signal tracking error)	
5.14.	Duration time for harmonic suppression (target harmonic content, duration time and reference signal tracking error)	
5.15.	BESU roundtrip efficiency	
5.16.	BESU scheduling execution	
5.17.	Standby losses	

The key measured parameters in the test report are the efficiency values of the power converters, overall energy conversion efficiency and maximum continuous output power of the prosumers.

Other important parameters are the stress values for prosumers (current, temperature), power quality measurements at the utility network side (accordance to IEC 61000), clearing times and duration times of different IEEE 1547.1 determined functions and ancillary tasks. From the measured parameters energy density and power density values can be calculated for prosumers and BESU.

9 Configurable values for prosumers

While the main parameters of bays are defined in the designing phase, some of the bay parameters and ancillary services can be adjustable for the prosumers. Table 4 presents an example configurable value list for the bays of the distribution substation, which can be adjusted through HMI. These parameters include nominal, maximum and minimum values of different prosumer side parameters, price and scheduling options when to consume or produce (charge or discharge). Maximum values cannot exceed the limits of the selected devices. Minimum values, in most cases, are limited due to economic reasons or capabilities of the devices. Positions 1.1-1.7 in Table 4 can be inserted and simulated in the MATLAB simulation environment.

Functional settings include different ancillary tasks, threshold values, time delays, time synchronization, BESU side preferences, event/history logging and status reporting/reading. Time delays should provide ride-through for low/high voltage and frequency values.

Table 4: Configurable values for prosumers

No.	Description of values	Value
1.	Prosumer parameter values	
1.1.	Nominal/min/max voltage	
1.2.	Nominal/min/max current	
1.3.	Nominal/min/max charging power	
1.4.	Nominal/min/max discharging power	
1.5.	Maximum capacity (e.g. Ah)	
1.6.	Capability selection for bay: V2G	
1.7.	Maximum DOD (%)	
1.8.	Nominal/min/max temperature	
1.9.	Nominal/min/max prices for charging	
1.10.	Nominal/min/max prices for discharging	
1.11.	Scheduling preferences for prosumers	
2.	Functional settings	
2.1.	Peak shaving option activation	
2.2.	PQ preferences (VAR management or harmonic suppression)	
2.3.	Target cos φ	
2.4.	Individual harmonic compensation list	
2.5.	Load balancing activation	
2.6.	Non-islanding voltage and frequency range	
2.7.	Time delays for ride-through of abnormal conditions	
2.8.	Response times to abnormal conditions	
2.9.	Time synchronization	

2.10.	Scheduling preferences for BESU management	
2.11.	Event/history logging	
2.12.	Status reporting/reading	

10 Future studies

Tallinn University of Technology currently develops a smart substation development methodology and constructing an experimental microgrid that enables us to study energy flows and data communication. Parts of the smart substation development methodology that are not covered in this paper need future studies. The basic functions and operation modes (including protection algorithms) such as energy transmission from the power grid to the energy storing system, EV battery charging, balancing power loads and other functions have to be developed, tested and analysed. The simulated management and control algorithms have to be fine-tuned and will be transferred to the substation RTU (Fig. 7). Data will be collected for further analysis using an iConcur Axiom software. Primary goals are to analyse the quality of energy flow, energy efficiency and harmonic levels during EV charging through the microgrid, electromagnetic compatibility related issues and to improve and apply the testing methodology. The analysis will indicate needs for modifications to be made in the microgrid structure to optimize and improve the overall efficiency and power factor levels in the system to ensure the quality of electricity in accordance with international standards.

Figure 7: View of an experimental setup with RTU devices for microgrid experimentations.

Practical applications will show possible drawback areas in the communication between the devices, which will then have to be solved with different control algorithms. Future studies will focus on development of a prototype microgrid and on possibilities to transfer energy to the common AC bus or to the power grid with synchronization related issues. Results from microgrid experiments will be published in future papers. Advice and warnings of issues to be aware of for smooth and accurate testing will be provided.

11 Conclusions

This paper has reviewed a developed testing method for distribution substations which form a microgrid with prosumers. Topology of the substations has been presented with an integrated AC and DC bus. The topology enables providing simultaneously services to prosumers, consumers and utility network. It has been proven through simulations that an integrated AC and DC bus (Fig. 1) can be the main topology solution for integrating prosumers with different nominal voltages to electric power grids. Simulation results have verified that bidirectional energy exchange between the utility network and prosumers can be used for peak shaving of utility networks loads.

In microgrid applications a distribution substation can be viewed as an energy router and it is the function of the substation's main controller in the higher level to determine when to utilize prosumers for ancillary services.

This paper has presented a new testing protocol for distribution substations. The testing procedure includes running computer simulations, prototype tests (using laboratory tests for substation and microgrid integration), factory tests and onsite tests.

Before constructing a real life substation, a smaller stand has to be constructed and examined. An experimental microgrid is being constructed at Tallinn University of Technology. Experiments with the microgrid will give vital data about charging/discharging algorithms and communication between the devices. These studies will enable us to construct a larger real life substation capable of supplying power to several prosumers that will be part of a microgrid or even a viable module of Smart Grid solutions.

Acknowledgment

This research work has been supported by European Social Fund (project "Doctoral School of Energy and Geotechnology II"), Estonian Ministry of Education and Research (project SF0140016s11), Estonian Science Foundation (Grant ETF9350), Estonian Archimedes Foundation (project AR10126), SmartGrids Era-Net (project GERA1) and European Regional Fund.

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa conducted by Foundation Archimedes.

References

1. M. Mägi, K.Peterson, and E.Pettai, "Analysis of Protection and Control Functions of Low Voltage Part of Substation for Smart Grid Applications," in "Proceedings of 8th International Conference 2012 Electric Power Quality and Supply Reliability: 2012 Electric Power Quality and Supply Reliability" Tartu 2012, 2012, IEEE, pp. 297-304.
2. G. Ritzer, N. Jurgenson, "Production, Consumption, Prosumption: The Nature of Capitalism in the Age of the Digital Prosumer," Journal of Consumer Culture (10:1), pp. 13-36, 2010.
3. J.M. Guerrero, M. Chandorkar, T-L. Lee, P.C. Loh, "Advanced Control Architectures for Intelligent Microgrids – Part I: Decentralized and Hierarchical Control; Part II: Power Quality, Energy Storage, and AC/DC Microgrids," in Industrial Electronics, IEEE, issue 99, 2012, pp 18.
4. M.Y. Nguyen, Y.T. Yoon, N.H. Choi, "Dynamic Programming Formulation of Microgrid Operation with Heat and Electricity Constraints," in Transmission & Distribution Conference & Exposition: Asia and Pacific, IEEE, 2009, pp 4.
5. C. Shumei, L. Xiaofei, T. Dewen, Z. Qianfan, S. Liwei, "The Construction and Simulation of V2G System in Micro-grid," Electrical Machines and Systems, ICEMS 2011, IEEE, 2011, pp 1-4.
6. D. Wu, C. Liu, S. Gao, "Coordinated Control on a Vehicle-to-Grid System," Electrical Machines and Systems, ICEMS 2011, IEEE, 2011, pp 1-6.
7. K. Kim, T. Yoon, G. Byeon, H. Jung, H. Kim, G. Jang, "Power Demand and Power Quality Analysis of EV Charging Station using BESS in Microgrid," Vehicle Power and Propulsion Conference, VPPC 2012, IEEE, 2012, pp 996-1001.
8. H. Laaksonen, K. Kauhaniemi, "Control Principles for Blackstart and Island Operation of Microgrid," in the Proceedings of the Nordic Workshop on Power and Industrial Electronics (NORPIE/2008), 2008, pp 8.
9. K. Bao, H. Zheng, "Battery Charge and Discharge Control for Energy Management in EV and Utility Integrations," Power and Energy Society General Meeting, 2012 IEEE, IEEE, 2012, pp 1-8.
10. P.B. Andersen, R. Garcia-Valle, W. Kempton, "A Comparison of Electric Vehicle Integration Projects," Innovative Smart Grid Technologies, 2012 3rd IEEE PES International Conference and Exhibition on, ISGT 2012, IEEE, 2012, pp 1-7.
11. J.F. Zhao, J.G. Jiang, X.W. Yang, "AC-DC-DC Isolated Converter with Bidirectional Power Flow Capability" in IET Power Electron., Vol. 3, Iss. 4, 2010, pp 472-479.
12. G.Y. Choe, J-S. Kim, B-K. Lee, C-Y. Won, T-W. Lee, "A Bi-directional Battery Charger for Electric Vehicles Using Photovoltaic PCS Systems," in Vehicle Power and Propulsion Conference VPPC10, IEEE, 2010, pp 6.
13. E.S. Dehaghani, S.S. Williamson, "On the Inefficiency of Vehicle-to-Grid (V2G) Power Flow: Potential Barriers and Possible Research Directions," Transportation Electrification Conference and Expo, ITEC 2012, IEEE, 2012, pp 1-5.
14. F. Marra, D. Sacchetti, C. Traeholt, E. Larsen, "Electric Vehicle Requirements for Operation in Smart Grids," Innovative Smart Grid Technologies, 2011 2nd IEEE PES International Conference and Exhibition on, ISGT 2011, IEEE, 2012, pp 1-7.
15. California Public Utilities Commission, "Test Plan and Procedures for Smart Distributed Resources Systems (DER) Interconnecting with Electric Power Systems (Draft)," May. 2013, pp. 18.
16. W. Bower, C. Whitaker, W. Erdman, M. Behnke, M. Fitzgerald, "Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems," Oct. 2004, pp. 46.
17. S. Chakraborty, W. Kramer, B. Kroposki, G. Martin, P. McNutt, M. Kuss, T. Markel, A. Hoke, "Interim Test Procedures for Evaluating Electrical Performance and Grid Integration of Vehicle-to-Grid Applications," Technical report NREL/TP-5500-51001, June 2011, pp. 29.
18. PNNL-22010, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems," Oct. 2012, pp. 60.
19. J. Butkowski, "Suggested Test Protocol for Distributed Energy Storage Systems at "The Edge of the Grid""," IEEE EnergyTech 2012, pp. 26.
20. Siemens, "Smart-Substation," [Online]. Available: http://www.industry.usa.siemens.com/topics/us/en/tradeshows/mobile sites/Documents/smart-grid-distributech/siemens-smart-substation.pdf. [Accessed: August 16, 2013].
21. ABB, "Power Quality Filters PQFI-PQFM-PQFS," [Online]. Available: http://www.abb.com/product/seitp329/ e83ed739e0daa5a9c1256f85004e548b.aspx. [Accessed: August 16, 2013].
22. Smart Substation, [Online]. Available: http://www.smartsubstation.eu/features/. [Accessed: August 16, 2013].
23. C. Gouveia, C. L. Moreira, J. A.. P. Lopes, D. Varajao, R. E, AraUjo, "Microgrid Service Restoration". Industrial Electronics Magazine, 2013, V7, No 4, pp 26-41.

24. Resource Dynamics Corporation, "Application Guide for Distributed Generation Integration: 2006 Update. The NRECA Guide to IEEE 1547," March. 2006, pp. 119.
25. L. S. Dudor, "Application and use of inspection checklists for factory and field inspection of electrical equipment" Petroleum and Chemical Industry Conference, Record of Conference Papers., Industrial Applications Society 35th Annual, 1988, pp. 105 – 118.
26. J. Bowen, "Industrial Substation Commissioning and Turnover Planning" - Petroleum and Chemical Industry conference, Applications Society 45th Annual, 1998, pp. 207 – 221.
27. "Secondary substation installation and commissioning specification", Scottish Power Energy Networks, 2006.
28. VDE-AR-N 4105, "Generators connected to the low-voltage distribution network – Technical requirements for the connection to and parallel operation with low-voltage distribution networks," Aug. 2011.
29. Man, E.A., "Control of Grid Connected PV Systems with Grid Support Functions," Master of science thesis, Aalborg University, Aalborg, Denmark, 2012, pp. 121.
30. "Factorized Power Architecture Delivers Maximum Efficiency and Density with Design Flexibility," [Online]. Available: http://powerblog.vicorpower.com/blog/powerblog/2012/10/factorized-power-architecture-delivers-maximum-efficiency-and-density-with-unique-flexibility/. [Accessed: August 16, 2013].
31. T. Korõtko, M. Mägi, K. Peterson, R. Teemets, E. Pettai, " Analysis and Development of Protection and Control Functions for Li-Ion Based Prosumers Provided by Low Voltage Part of Distribution Substation," 8th International Conference – Workshop Compatibility and Power Electronics CPE 2013, Ljubljana, Slovenia. IEEE, 2013, pp. 19-24.
32. J.M. Magraner, "Ultra-Fast DC Charging Stations" in the ECPE Workshop on Power Electronics for Electric Vehicles", 2011, 23 p.
33. Panasonic, "Lithium Ion Batteries Technical Handbook," 2007, [Online]. Available: http://industrial.panasonic.com/www-data/pdf/ ACI4000/ACI4000PE5.pdf. [Accessed: August 16, 2013].

Arrived: 17.9.2013
Accepted: 8.5.2014