Conceptual Study for Open Energy Systems: Distributed Energy Network Using Interconnected DC Nanogrids

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***Abstract*—We describe the general concept and practical feasibility of a dc-based open energy system (OES) that proposes an alternative way of exchanging intermittent energy between houses in a local community. Each house is equipped with a dc nanogrid, including photovoltaic panels and batteries. We extend these nanogrids with a bidirectional dc–dc converter and a network controller so that power can be exchanged between houses over an external dc power bus. In this way, demand-response fluctuations are absorbed not only by the local battery, but can be spread over all batteries in the system. By using a combination of voltage and current controlled units, we implemented a higher-level control software independent from the physical process. A further software layer for autonomous control handles power exchange based on a distributed multiagent system, using a peer-to-peer like architecture. In parallel to the software, we made a physical model of a four-node OES on which different power exchange strategies can be simulated and compared. First results show an improved solar replacement ratio, and thus a reduction of ac grid consumption thanks to power interchange. The concept's feasibility has been demonstrated on the first three houses of a full-scale OES platform in Okinawa.**

***Index Terms*—DC–DC converter, dc power distribution, dc power transmission, interconnected power system, microgrid, power system control, smart grid.**

I. Introduction

A HIGH penetration of renewables requires profound changes to the current grid system [1]. Indeed, the conventional ac grid system is a rigid architecture built around centralized fossil fuel or nuclear power plants that distribute energy over long transmission lines, substations, and distribution network before arriving at the end users. The conventional grid is increasingly becoming a bottleneck for expanding the share of renewables. Most promising renewable sources like solar and wind are geographically distributed (distributed energy resources—DERs) and often depend on weather or environmental condition. However, distributed generations (DGs) cause problems such as voltage rise and protection problem in the utility grid [2]. The variability and intermittency in power output are posing a serious issue for managing the demand-response requirements for electricity networks. This is especially true as plug-in hybrid electric vehicles (EV) add a large stochastic load onto the system [3]. Large and fast energy storage units (most promisingly Lithium-ion batteries [4]) are needed to handle the transient mismatch of generation and consumption.

To propose solutions for these challenges, a wide range of new energy grid systems, often grouped as smart grids [5], are now emerging. Though there is no standard categorization [6], we define three main approaches: 1) microgrid; 2) nanogrid; and 3) virtual power plant (VPP).

Microgrids are promising solutions for integrating large amounts of micro-generation by reducing the negative impact to the utility network [7]. In general terms, microgrids can be defined as structures that combine DG units, energy storage systems (ESSs), and loads [8]. Microgrids including batteries allow to shift peak demand and flatten the consumption pattern. While their architecture may vary greatly depending on the type or number of building blocks as well as the application context [8]–[10], a clear distinction can be drawn between ac and dc-based microgrids. Justo *et al.* [8] concluded that even though ac microgrids are now predominant, the number of dc microgrids is expected to increase in the coming years as they will soon be the right candidates for future energy system.

Nanogrids can be seen as smaller and technologically simpler microgrids, typically serving a single building or a single load. As they face less technical and regulatory barriers than their microgrid counterparts, substantial deployment is already undergoing [11]. This is why compared to microgrids, nanogrids are often seen as a bottom-up approach, well suited also for off-grid areas and with a clear preference for dc solutions [11].

However, to prevent both power outages and wasting generated electricity, most microgrids/nanogrids include a utility grid connection. In Europe, where the utility grid is advanced and DER are widespread, feed-in-tariffs have been more attractive compared to purchasing a storage unit, but they are decreasing yearly [8] because the higher the intermittency of power sources, the higher is the costs for upgrading

Manuscript received March 26, 2014; revised August 8, 2014, August 13, 2014, and December 8, 2014; accepted February 15, 2015. Date of publication March 27, 2015; date of current version June 18, 2015. This work was supported in part by the Subtropical and Island Energy Infrastructure Technology Research Subsidy Program of the Okinawa Prefectural Government. Paper no. TSG-00274-2014.

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Digital Object Identifier 10.1109/TSG.2015.2408603

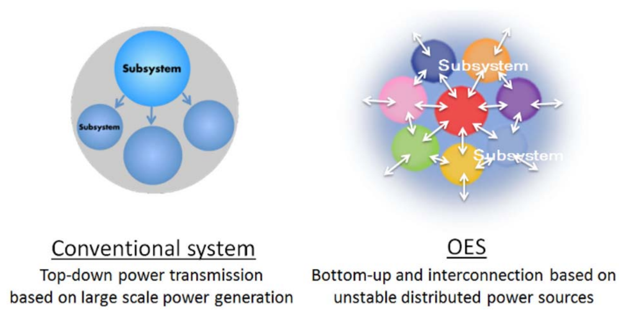

Fig. 1. OES concept compared to conventional approach.

the conventional grid and including energy storage [12]. Interconnections and energy storage facilities are required to reduce the stress that intermittent renewables cause on primary generation such as nuclear and thermal [13], [14]. Thus, the future energy grid in those areas is predicted to be based on the various DG units, storage devices, and controllable loads that are connected with advanced information and communication devices such as automated meter infrastructure. In those systems, DG units, ESS, loads, and also microgrids are aggregated in clusters and can be seen as VPPs [15] that can then be treated as single entity. VPP can be considered as top-down approach that taps into the existing grid via smart meters and software to add the intelligence necessary to manage demand-response [8]. The aim is to remotely and automatically dispatch and optimize DG via an aggregation platform linking retail to wholesale markets [16]. For supporting both a wide range and flexible number of DERs, VPPs must be both loosely coupled and generally adopted by all players requiring standardization of communication [17].

All together, nanogrids and microgrids are usually bound to fixed building blocks, and VPPs are essentially software solutions bound to the existing utility grid infrastructure. In this paper, we propose Open Energy Systems (OESs) as a new type of scalable and bottom-up distribution network that shares some characteristics of all three approaches: building blocks are a flexible number of dc nanogrids, interconnected via a local dc power grid and controlled in a distributed way see the Appendix for comparative table. The general concept may be seen as a multilevel dc grid system whose two-level implementation we investigate. It provides both hardware and software for exchanging energy in-between dc nanogrids of a local community so that we can spread fluctuations over the community without needing to feed-in energy to the utility grid. Each house is equipped with one subsystem, a dc nanogrid including batteries, that is connected to a dedicated, shared dc power bus as well as a communication line allowing power exchanges within a community.

The concept is an application of open systems science [18], [19] to energy distribution: instead of the conventional top-down approach requiring a grid infrastructure and large scale power transmissions on the top, OES is based on independent subsystems that are interconnected to share power from unstable distributed sources (Fig. 1). It is called open because the connections can vary freely and energy can be exchanged both among subsystems as well as with the environment, for instance, by harnessing solar energy.

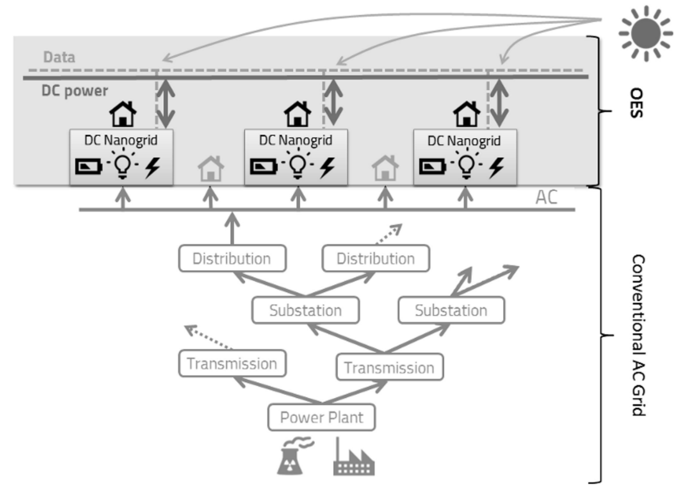

Fig. 2. OES as a dc microgrid made of interconnected dc nanogrids that can be developed in parallel to the ac utility grid.

In this paper, we first describe the OESs concept and architecture, that is, the components of a standalone nanogrid as well as the interconnections of such subsystem to make an OES. Then, we introduce the layered control scheme (from the lowest physical layer of energy transfer to the highest system control layer) which constitutes a main research focus of this paper. First simulation results of our system are shown. Finally, an overview of our laboratory prototype and the experimental platform that is currently under development in Okinawa is given.

II. OES as Multilevel DC Grid System

The concept and advantages of interconnecting microgrids have been analyzed by Falvo and Martirano [20] and Brenna *et al.* [21], who suggested sustainable energy microsystems as a type of multilevel grid systems. They classified the level of integration among the subsystems and showed promising results in their preliminary analysis [21]. While the main concepts and theoretical analysis are valid for this paper as well, we propose a system where there is no direct connection to the utility grid (Fig. 2). Indirectly, subsystems may be internally connected to the utility grid that would then serve as auxiliary power source as it is the case for common commercially available residential systems, but this does not impact OES. We do not feed-in electricity to the utility grid, meaning that there is no power trading with the utility grid. Power trading and load shedding is exclusively done within the OES community over our own system, a dc-based distributed grid. This allows us to develop a parallel, utility-independent grid without compromising on network reliability for residents, a crucial requirement for our real platform in Okinawa.

The OES is build on two dc layers: 1) the dc nanogrids installed in each house; and 2) the dc microgrid that connects the nanogrids over a higher voltage dc power bus line. We chose dc for both levels because of the following reasons.

1) Power merging is easier and so is the system analysis (no frequency, phase, or waveform control, thus no synchronization) [8].

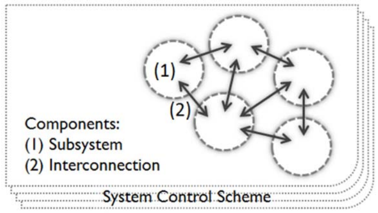

Fig. 3. OES design outline.

2) More efficient transmission lines and improved system stability because of the absence of reactance and external disturbances [8].
3) Wide variety of "raw" electricity output from renewable energy can be easily connected to a dc power bus line and batteries without requiring ac/dc conversions. The same is true for a vast variety of consumer equipments that could be seen as dc loads (approximately 80% of loads in commercial and residential structures are now dc [22]) which results in an increasingly attention for dc distribution [8].
4) Progress of dc conversion technologies has led to efficiencies above 90% making it practical to convert voltage sources to current sources (over 94% efficiency for 48–380 V conversion at 2 kW using a resonant-type bi-directional dc–dc converter [23]).

Thus, the OES can be structured into three parts (see Fig. 3).
1) *Subsystem Design:* Standalone nanogrid including batteries and ac grid connection.
2) *Interconnection Between Subsystems:* DC power bus and communication lines.
3) *System Control Scheme:* Software development on all layers.

III. System Components

This section addresses the general hardware architecture including the choices made for subsystem design and interconnections. We also generalize OES concept and describe how it can be scaled up for future applications.

A. Subsystem Design

The core element of each subsystem is a modular dc nanogrid at least one of each of the following types of modules.
1) *Power Sources:* photovoltaic (PV) panels, wind turbines, generators, and ac input.
2) *Power Loads:* ac loads and/or dc loads.
3) Storage devices such as batteries that can act either as load or power sources.

A controller to get basic monitoring and control of all internal modules is also needed.

In this paper, we use basic, small-scale distributed nanogrid systems that are commercially available and are housed in a single rack (for more details on the physical modules specifications refer to Section VI). We use two external power sources, ac input and PV input, and one main power load (ac). DC loads are still under investigation. We do not feed surplus electricity into the utility, so from a utility perspective, all subsystems are simple power consumers. Thus, the core nanogrid includes the following modules:

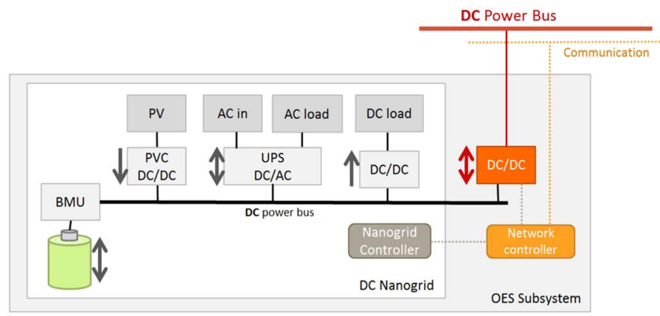

Fig. 4. Modular view on subsystem: a dc nanogrid including the additional modules for dc interconnection (in orange).

1) PV panel and PV charger (PVC = a dc–dc converter including maximum power point tracking control);
2) three battery units (3.6 kWh) and a battery management unit;
3) an inverter allowing to use ac power for input as well as to supply energy from the battery to ac loads—both functions are combined in an uninterruptible power supply module;
4) a nanogrid controller that controls all internal modules over an internal communication line.

Internally, all modules on the rack are connected together over the same dc bus whose voltage is determined by the battery voltage—nominal 51.2 V. The system can therefore be considered as a dc microgrid with bipolar configuration and including an ESS as described in [8]. We converted this basic standalone nanogrid to a full OES unit—that is a local system able to exchange energy with other systems over a designated, external dc power bus by adding following two modules:
1) a current and voltage regulated bidirectional dc–dc converter (resonant-type);
2) a network controller that communicates with the internal nanogrid controller and that can monitor and control the dc–dc converter. It is also responsible to establish the network communication and serves as interface to all hardware units. This logical unit is the basis of building robust software for distributed power exchange.

The modular subsystem is presented in Fig. 4. The advantage of such a modular design that separates the core nanogrid from the interconnecting modules is that, in principle, any kind of nanogrid that fulfills the previously mentioned requirements can be used as long as the interface between nanogrid controller and network controller is adapted so that a minimum set of monitoring/control functionalities can be accessible over the network. The nanogrid controller must guarantee that under no circumstances the internal safety is compromised. The dc interconnection shall be cut and the subsystem shall fall back to standalone mode if anything goes wrong. All higher-level networking logic are designed to be completely independent from the lower-level software and the internal functioning of the microgrid, allowing a clear layering and thus freeing the

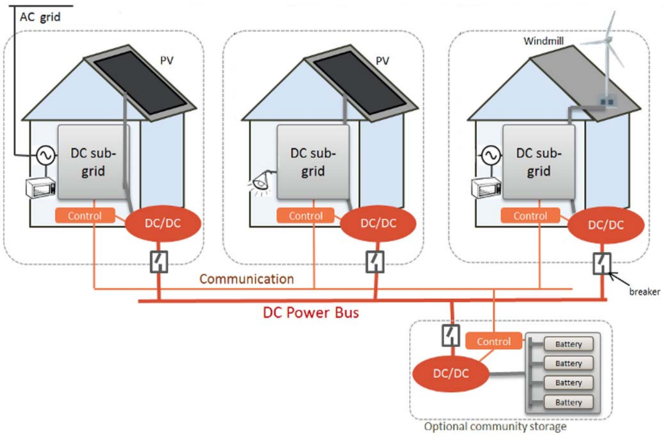

Fig. 5. General system layout for OES.

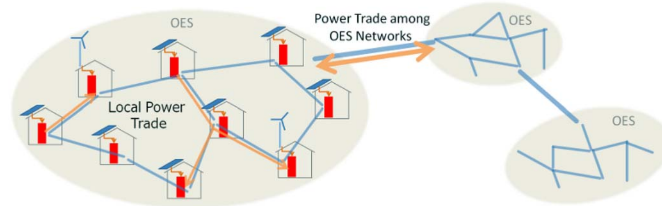

Fig. 6. Proposition of scaling up OES by making a three-layered dc grid.

conceptualization of a power exchange strategy from low-level physical processes.

B. DC Interconnection Between Subsystems

Subsystems are interconnected via two lines.

1) DC power bus line that is laid out from house to house including a dc breaker that can disconnect the house from the others. A bipolar dc-link configuration [8] between ground and a voltage of 380 V (or 350 V depending on setup) is being used. Three hundred and eighty volts is chosen because it is the voltage that EMerge Alliance [24] and the European Telecommunications Standards Institute is expected to set as standard voltage for building-wide dc wiring.
2) *DC Grid Communication Network:* In form of a local area network (LAN) to which connects the network controllers based on Internet protocol (IP). Implementation details are described in the next section on system control scheme.

C. Generalization and Scalability

The OES architecture is not limited to the previously explained system components. This current setup is used in our simulations and prototypes for simplicity and reliability reason. However, the most promising future applications such as remote islands or off-grid areas require a flexible and adaptive architecture.

1) Generalization: While our current setup is rather homogenous in terms of subsystems, the physical setup within each house for future setups can heterogeneous, that is, each unit may have a different internal structure (Fig. 5). For instance, it may or may not have ac connection or even feed-in electricity to the ac grid if it is more advantageous. It may use solar panels or wind energy. Battery size may be different. The more units and the more different types of energy sources, the more unit-specific fluctuations can be attenuated across the network and thus make the system more reliable and reduce dependency on the ac grid. Different types of subsystems such as a community storage system for backup or emergencies can be connected, but they all must have the same network interface and follow the same policy. Hence, this interface must be general and flexible, but still respect internal safety under any circumstances.

2) Scalability: As the number of subsystems connected to the same network increases, distances between houses become bigger and resistive losses on the power bus line (380 V dc) reduce efficiency. It gets more complicated to keep the bus voltage stable and also distributed control becomes more complex and increases delays. Thus, rather than increasing the size of one OES by multiplying the number of connected units, we can increase the system size by connecting several OES systems together by using the same type of strategy as for connecting subsystem, but one layer higher (meaning higher voltages and conversion capacities). An entire OES community could share energy with another neighboring OES community using a dedicated high voltage dc power bus and appropriate dc–dc converters (Fig. 6).

TABLE I
SOFTWARE LAYERS

Level	Description
4	**Higher Level software:** Visualization, evaluation, optimization
3	**Network wide autonomous power management**: automatic exchanges
2	**Unit to unit power flow and communication:** for n-to-n power exchange
1	**Subsystem control**: monitor and control all internal modules

IV. SYSTEM CONTROL SCHEME

This section explains the system control scheme from a practical implementation side, that is, mainly the software implemented in the network controller. For it, we layered the complexity and approached it bottom-up as shown in Table I. The first three levels are run on the network controllers. Level 4 is different from the other three in the sense that it is developed either on top or on parallel to the first three levels. Note that when talking about software, we refer to subsystem as a "unit." Also, this is ongoing research and especially levels 3 and 4 may be subject to modification.

A. Subsystem Control

To fully access and control all modules within one subsystem, an externally accessible communication interface is implemented in the network controller. This interface allows to digitally control all modules by making abstraction of the

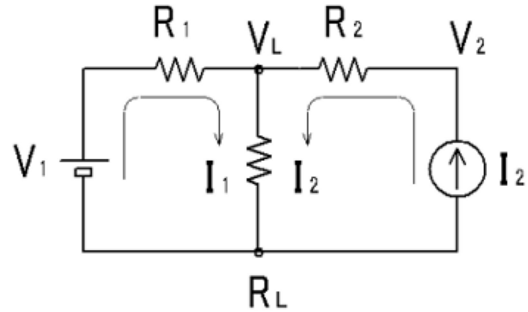

Fig. 7. Voltage and current source on bus line (R_1 and R_2 are wiring resistances and R_L is load).

specificities of each subsystem. In practice, we implemented two communication interfaces: one protocol ensures the communication to the already existing nanogrid controller which indirectly gives access to internal modules and combines them in one simplified interface. In the case of our dc nanogrid, only very limited control is available through the internal controller (i.e., switching or mode setting). The message transfer uses on serial communication (ModBus protocol).

The other one is communicating with the bidirectional dc–dc converter and hence this protocol will be responsible for handling not only dc–dc converter parameters but also the commands of the actual power exchange command and for monitoring the power exchange. The messages send between the controller and converter use RS485 protocol.

For both communication interfaces, we also implemented an external interface that can be accessed via a HTTP RESTful Web-service built on the transmission control protocol (TCP)/IP protocol that is used in layer 2.

We performed several series of tests to ensure robustness and safety with parameter setups or unexpected connections in order to ensure that hardware limitations are respected under any condition.

B. Unit to Unit Power Flow and Communication

We implemented a general procedure using the dc–dc interface of layer 1 that allows us to digitally control the power flow between subsystems by making abstraction of the physical commands or phenomena. The underling principle is described in the following paragraph.

There are multiple ways to merge dc power in order to achieve a controlled *n*-to-*n* power exchange. One of the schemes is to add dc voltage relying on the internal resistance of the dc voltage sources and line resistance which is widely used for the dc electric railway system. The other is to assign a single dc voltage source that determines the voltage of the power line and provide an arbitrary number of dc current sources connected to the power bus. An example circuit with one constant voltage (CV) source and constant current (CC) source is shown in Fig. 7. Indeed, if the wiring resistance R_1 is considered much smaller than the load R_L, then (2) shows that the wiring resistance R_2 has no effect, as if the current from the CC source was supplied from the CV source

$$V_L = R_L(I_1 + I_2) \text{ and } I_1 = \frac{V_1 - V_L}{R_1}.$$

Hence

$$\left(\frac{R_1 + R_L}{R_1}\right)V_L = \frac{R_L}{R_1}V_1 + R_L I_2.$$

If

$$R_1 + R_L \cong R_L \tag{1}$$

then

$$V_L = V_1 + R_1 I_2. \tag{2}$$

In our implementation, we adopted the latter scheme because: the latter system is analytically consistent to boost current of voltage power source [see (2)] by keeping the voltage stabilized without needing any critical control system. Progress of the dc–dc converter technology made it practical to convert voltage source to current source [25]. In our case, even though all converters can work both in voltage regulated (CV) or current regulated (CC) mode, only one converter is dynamically chosen to work in voltage regulated mode and thus keep the bus voltage constant. All other dc–dc converters are either on stand-by or on current controlled mode. The master converter acts either as load or as source depending on the sum of all other units' currents. In this way, it always keeps the bus voltage constant during power exchanges. The procedure of election of the master converter is carried out on the third layer (see next paragraph).

The above explained strategy has been experimentally tested with three sets of bidirectional dc–dc converters that can be used both in CC and CV mode (up to 2.5 kW). Experimental tests show that voltage and current can be safely controlled using this scheme without requiring higher intelligence. Note that in practice, several modifications to the dc–dc converter were necessary to implement this strategy.

The communication is assured over a LAN using TCP/IP. A dc-powered hub is used at each subsystem that is directly powered by the battery. To avoid a hub being down because of empty batteries and thus causing the communication line to be down, we use a power over Ethernet like concept so that the hub could continue operating in this case by using its direct neighbor's power.

The power exchange procedure is viable as long as our system has a limited number of subsystems that are geographically close so that assumption (1) holds. To scale up the system we suggest the approach described in Section III-C but its practical feasibility is not addressed in this paper.

C. Network Wide Management

This layer is responsible for performing the tasks required for the OES to handle power exchanges fully autonomously (without human intervention). The difference with most other systems, is that this software is not centralized on one special logical unit, but distributed over the subsystems that communicate with each other over message exchanges (combination of TCP and user datagram protocols). To achieve this, we got inspired by one of the most widely adapted decentralized architectures: pervasive peer-to-peer networks as described in Tannenbaum's [26] book on *Distributed Systems*. Peer-to-peer systems are horizontally distributed meaning that all processes

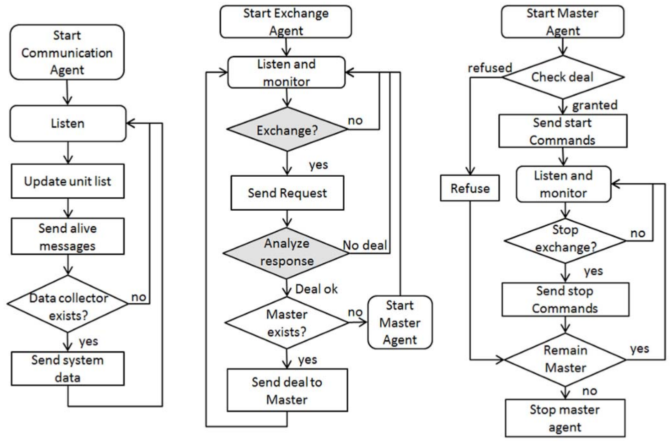

Fig. 8. Simplified flowchart of three main agents.

or systems are equal from a high-level perspective and interaction is symmetric [26]. They ensure independence of each system and avoid bottlenecks.

We adopted an approach that could be seen as a multiagent system (MAS). MAS has been shown to work well to control intelligent grid systems made of less-intelligent entities (local controllers) [15], [27]–[31]. We split the software into three main tasks that are taken care by a subprocess, an agent. A simplified flow chart is shown in Fig. 8.

1) Communication Agent: Configuration and Communication Management: In a distributed system, the setup, management, and connections are crucial but often tedious. The aim is to implement a procedure to dynamically expand or reduce the system's size when a new unit connects or disconnects to achieve a plug-and-play like system. For this, all units are subscribed to a multicast address to which they periodically send alive messages containing system information such as their IP. All units continuously listen to these messages and keep a list of connected devices that is continuously updated (loosely based on universal plug and play principles in [32]). On a later stage, a layer of authentication may be added before adding a new device to the list.

This agent is also responsible to reply to multicast messages from an eventual data collecting unit (see Section IV-D).

2) Exchange Agent: Power Negotiation Between Units: This agent is the core part of the software because it contains the power exchange strategies or also called scenarios. Its development is still ongoing. For now, we present only the simplest exchange strategies based on the battery state of charge (SoC).

Each unit continuously monitors its internal parameters and checks according to the predefined scenario if a power exchange is desirable. If so, an exchange request is send out to all units. Then, the responses are analyzed, an exchange partner is chosen (if existing) and a power deal is agreed on. The deal must be executed and commanded by a master which is the unit that will take the voltage control over the bus line (see below). If no master exists, the requesting unit will become master for the time of the power exchange. Only the master unit can send the commands to control the dc–dc converters.

TABLE II
MAIN EXCHANGE STRATEGY

Request strategy	Trigger level
Start exchange	$charge: \ SOC < 10\%$ $discharge: \ SOC > 70\%$
Stop exchange	$charge: \ SOC > 40\%$ $discharge: \ SOC < 30\%$

Scenarios define the exchange strategy that is used to make a decision on whether to request or accept a power deal (decisions in gray boxes on flow chart in Fig. 8). The currently used scenario is based on SoC trigger levels as shown in Table II. A request is send out when a trigger level is reached. A request from another unit is accepted for any SoC value between the start and stop trigger. The amount of power exchanged is currently fixed at a level where conversion losses are minimal (1 kW). No system wide information is needed, making the system fully distributed.

These scenario files are extensible and could include a more sophisticated, optimized decision making of when to request or accept a power exchange. For instance, the recent power balance, i.e., the change in SoC $\sum P_i = \Delta\text{SoC}$, or also previously collected data from our weather station or system log data can be used for optimization of the power exchange timing as well as the amount of power to be sent. Future research and simulations are required.

3) Master Agent: Power Exchange Command and Supervision: A temporary master is needed to command and supervise each power exchange. Only one master agent can be in system. Once a master is selected for a power exchange, it receives the deal from the exchange agent. The master checks safety and feasibility for example if the exchange does not exceed the bus current limitation. If the deal is safe it is accepted and the master sends the command request to the layer 2 of the concerned subsystems. For the first deal, the discharging unit will take on the role of voltage controlled node (CV—master node) and ramp up the bus voltage. The charging unit as well as all subsequent deals are regulated by controlling the current (CC). If a power exchange is terminated (either on request of a concerned subsystem or because of safety reasons), the CV node is transferred to another discharging unit and if there is no other exchange is ongoing, the master frees the bus voltage control and gives up its role as a master agent. Using this approach, called dc bus intermittent control, operating losses of the dc–dc converters can be significantly reduced.

D. Higher-Level Software

The previously explained three layers provide the functions for the autonomous operation of the OES. We aim at providing a general platform that can serve for studying exchange algorithms but also for wide range of data analysis as well as for commercial deployments. For this, we implemented a data collecting unit that does not require any configurations and automatically adapts to newly added or removed subsystems. It servers as an central interface to the entire OES. Currently, it is accessed to save system status and action logs to a centralized

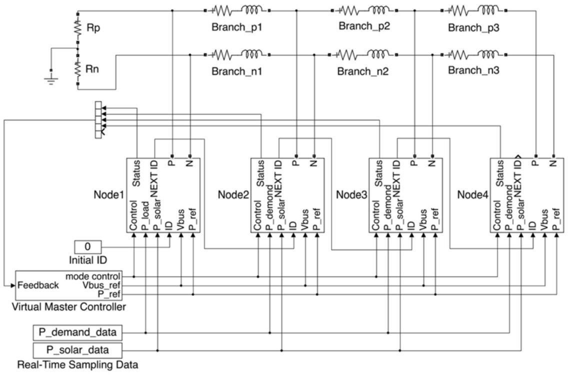

Fig. 9. Physical simulation model of an OES consisting of four subsystems.

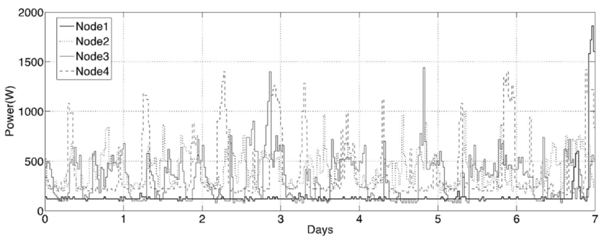

Fig. 10. Electricity demand data for four houses.

TABLE III
SIMULATION PARAMETERS

Item	Property	Value
Cable resistance	$Size : 8mm^2$	$2.3\Omega/km$
Cable length	$Nodetonode$	$100m$
Balance resister	$1pair/system$	$100k\Omega$
DC-DC converter	$loss : min(standby)$ $loss : min(operation)$	$5W$ $70W$
DC-DC converter	$efficiency$	95%
Solar PV	$Max/4nodes$	$213kWh/week$
Solar PV	$Peak/node$	$1kW$
Electricity demand	$Node1$ $Node2$ $Node3$ $Node4$	$25kWh/week$ $69kWh/week$ $56kWh/week$ $63kWh/week$

TABLE IV
SOC TRIGGER LEVELS USED FOR CONTROLLING POWER EXCHANGE

Exchange strategy	Trigger level
B: active SOC-based : start	$charge:\ SOC < 10\%$ $discharge:\ SOC > 70\%$
B: active SOC-based : stop	$charge:\ SOC > 40\%$ $discharge:\ SOC < 30\%$
C: system SOC balancing: start	$SOC > 90\%$ $SOC < 10\%$ $\vert SOC - SOC_{avg}\vert > 25\%$
C: system SOC balancing: stop	$\vert SOC - SOC_{avg}\vert < 1\%$

database that can then be used for data analysis (see Section VI for more details on current implementation).

This paper focuses on providing a general, configurationless and flexible interface for higher layers. Future research should aim at analyzing efficiency, optimizing power transfers, and identifying bottlenecks as to increase overall energy self-sufficiency of the community. Furthermore, active consumer interaction and market oriented systems may be added.

V. SIMULATIONS

While the OES architecture and feasibility is being verified in practice (see Section VI), physical simulations may verify the effectiveness of exchanging energy between subsystems and evaluating the impact of exchange strategies on the percentage of energy that could be replaced by renewables generated within the community.

We made real-time, multidomain simulations in MATLAB/Simulink/SimScape consisting of four subsystems or nodes. Based on EV technologies, we build a physical model of each subsystem and the interconnections with different kinds of architectures (Fig. 9) and exchange strategies presented in [33]. In this paper, we present only parts of the preliminary results that are most relevant for the previously described architecture and strategy.

A. Simulation Input Data

As consumption data, we used seven days real-demand data for four houses that we extracted at random from the real electricity demand annual database of 100 houses in Kyushu, Japan, subscribed to a 6 kVA pay-as-you-go deal (see Fig. 10). We generated solar power generation according to (3), where P_{peak} is set to 1 kW so that photovoltaic energy is approximately equal to demand

$$P_{PV} = \begin{cases} P_{\text{peak}}\left(-\cos\left(\frac{2\Pi t}{T_{\text{day}}}\right)\right), & \cos\left(\frac{2\Pi t}{T_{\text{day}}}\right) < 0 \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

DC–DC converter losses and other system specific parameters are chosen as shown in Table III.

B. System Configuration Control

Different types of power exchange strategies were implemented: system A does not use any dc power exchange. Systems B and C exchange dc power according to SoC trigger levels shown in Table IV. System B only uses information about local SoC level for requesting a power exchange. System C also uses the average SoC level, SoC_{avg}, across the entire OES system to determine if a power exchange is desirable. When no power exchange is taking place, the bus voltage is discharged in order to reduce the losses due to the operating consumption of the dc–dc converter (dc bus intermittent control). The power to be exchanges is fixed at a constant value of 1 kW.

C. Simulation Results

To compare the different systems, we define the solar energy replacement indicator K_{solar}

$$K_{\text{solar}} = \frac{E_{\text{demand}} - E_{\text{ac}} - E_{\Delta\text{SoC}}}{E_{\text{demand}}}. \tag{4}$$

Since this indicator takes into account the losses from dc–dc converter as well as the ones of the battery cycle, it reflects the actual contribution of solar power. It does not take into account the dc/ac conversion loss because it is not of interest in this discussion.

TABLE V
SIMULATION RESULTS

System	DC bus intermittency ratio	DC-DC Converter loss	Wasted Solar Energy	Renewable Replacement ratio K_{solar}
A	-	-	14%	84%
B	83%	8.3kWh	5%	91%
C	79%	10.3kWh	0%	95%

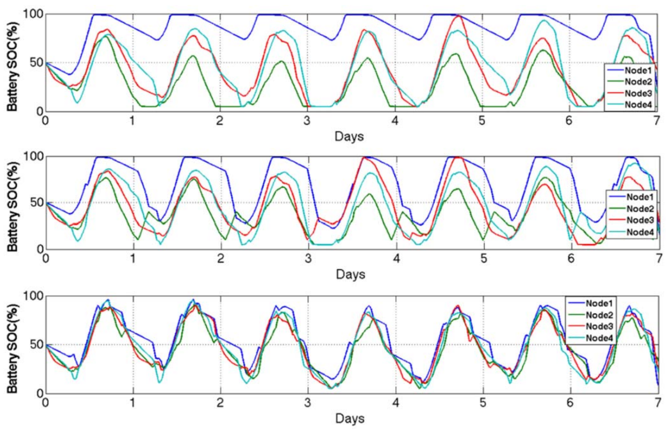

Fig. 11. Simulated battery SoC for systems A, B, and C, respectively.

We observe an increase from 84% to 91% or 95% in the solar replacement ratio depending on the strategy. This improvement can be explained by looking at Fig. 11. Node 1 has a relatively small consumption which causes the battery SoC level to be full from early afternoon. Without exchanging energy, the solar energy generated by this node in the afternoon is wasted. On the other hand, nodes 2 and 3 will run out of battery in the early morning and require charging from ac grid supply. Systems B and C are programmed to automatically transfer the energy between the nodes when any of these two cases happen and thus reduce wasted solar energy. In system C reaches 95% of solar replacement ratio. We observe that 100% of the solar energy is used; the remaining 5% are due to conversion losses in the dc–dc converter itself.

Further simulations show that the solar replacement ratio increases as the number of nodes in the system increases but when nearing ten unit, it converges to the theoretical limit that corresponds to case of centralizing all capacities of resources and loads. To increase the ratio further, bigger and more heterogenous resources or load shedding are required.

VI. FEASIBILITY STUDY

This paper is conducted bottom-up starting from the practical feasibility and aiming at directly testing assumptions on real appliances. An three-subsystem experimental prototype in the Sony Computer Science Laboratories (CSL) in Tokyo, another three-subsystem prototype at the Okinawa Institute of Science and Technology (OIST) as well as our full scale platform at OIST are briefly presented in the following paragraphs.

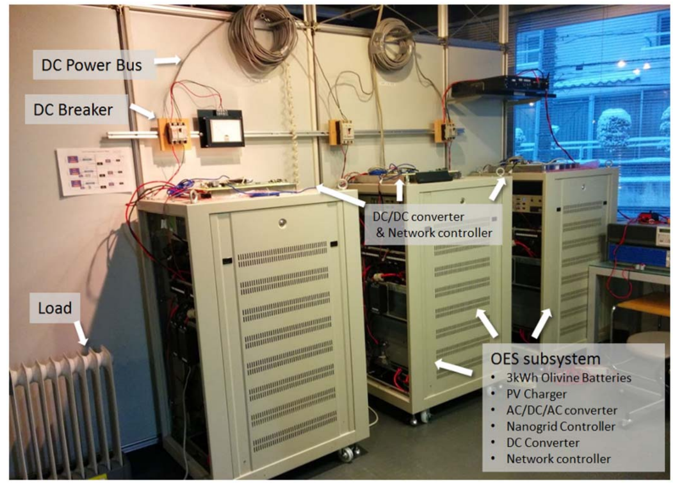

Fig. 12. Laboratory prototype at CSL in Tokyo.

A. Laboratory Prototype

The laboratory prototype (Fig. 12) has served to test basic assumptions on how to physically control the power flow from an analogue and digital point of few and to program the network controller. It is made of the following components.

1) three dc nanogrids (installed in one rack):
    a) 3.6 kWh (3 × 1.2 kWh) olivine Lithium-ion iron phosphate batteries (45–57.6 V);
    b) PV charger (2 kW output);
    c) ac/dc (2.5 kW) and dc/ac (3.5 kW) converter;
    d) internal dc power bus connecting all modules (nominal 51.2 V);
    e) bidirectional dc–dc converter (rated output power 2.5 kW);
    f) internal nanogrid controller;
    g) network controller (Linux OS connected to a Ethernet LAN).
2) dc breakers (10 A dc);
3) dc power bus line between units of 40 and 60 m (nominal voltage 350 or 380 V);
4) ethernet LAN (including hub);
5) *testing Equipment:* dc load, ac load, and dc power supply to simulate loads and energy sources.

B. Full Scale Experimental Platform at OIST

The same physical setup but including PV panels is also used at the prototype in the pump room (technical facility room) at OIST (Fig. 13). There, the subsystems are connected to solar panels installed on the entrance of the university (5 kWp, 2.5 kWp and 2.5 kWp respectively). The output of the one units is used for powering projectors and one for powering an air conditioner. The output of the third is connected to the ac input of the second. This connection setup results in an unbalanced power usage. The three units are interconnected over a dc power bus line and communication line which allows to send power to balance the power consumption. All power exchange can be remotely controlled and visualized.

By the end of 2014, the main platform (Fig. 13), that is 19 inhabited houses at OIST, will be equipped with solar

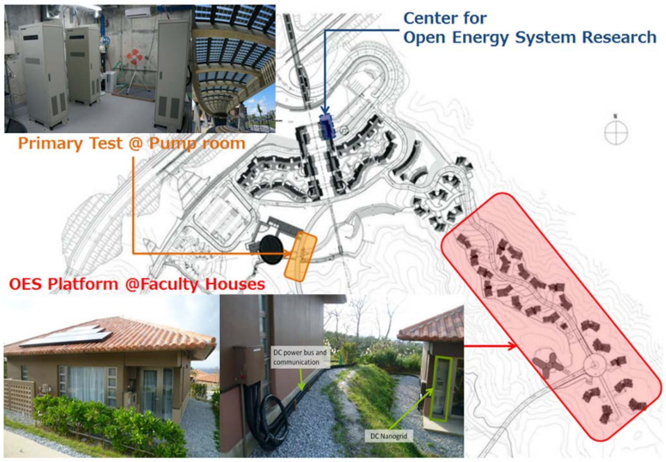

Fig. 13. OES platform at OIST: primary test site and full scale platform at faculty houses.

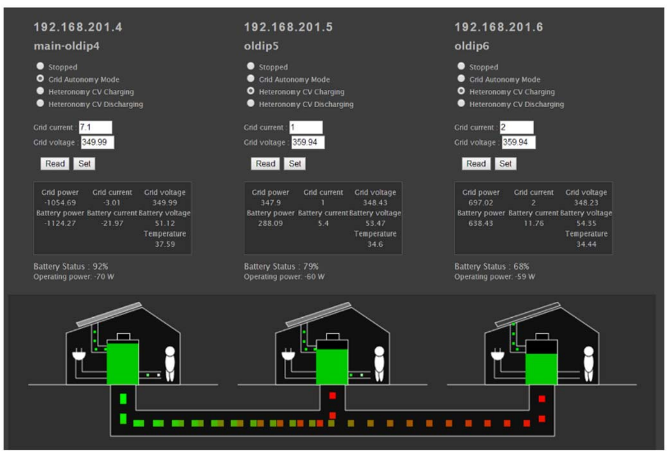

Fig. 14. Visualization of an *n*-to-*n* power exchange using three subsystems.

panels (2.8 or 4.3 kWp) as well as identical dc nanogrids as described for the laboratory prototype. They will be connected via a dc power bus (nominal 350 or 380 V). On first three connected family houses a life demonstration of *n*-to-*n* dc power exchanges using the visualization (Fig. 14) has been given on the First International Symposium of OESs (January 14–15, 2014 at OIST). This was the first step to proving the technical feasibility and safety of this kind of setup. However, tests on the subsystems and connection of the remaining houses are still ongoing.

In terms of software, we have build real-time visualization of the energy flow within subsystems and in-between subsystems. An anonymous full system visualization version will shown to the community including a subsystem view for the residents (restricted to their own subsystem). A full system and individual visualization including a manual control interface can be accessed by researchers or administrators (see three-unit version on Fig. 14). Combined with previously collected data, these interfaces are the basis for overall system evaluation.

Please note that the implementation of the software layers 3 and 4 is still ongoing. Even though the logic described above is roughly respected, in practice, two of the software agents are running on the same physical unit which facilitates greatly development and debugging. Nevertheless, even in the current prototype all units have completely identical software, they are plug-and-play (no manual configuration needed). Further software development and safety and fault tests are needed before running extensive long term tests using the autonomously controlled OES in inhabited houses.

VII. Conclusion

As the demand for sustainable energies continues to increase, it is important to find ways not only to generate but also to distribute the power coming from inherently distributed and unstable power supplies such as renewable resources. This paper analyzes a new type of dc based, distributed interconnection of dc nanogrids. In this paper, we propose a new concept, both in terms of hardware and software architecture and show the benefits on four-node simulations using physical model. We further demonstrate the feasibility on a full-scale platform, which is one way of putting the concept in practice. Note that the research is still ongoing and some parts of the concepts still need to be studied further. In the future, this paper will constitute the basis of higher-level intelligent exchange strategies using weather forecasts, predictions for peak cutting or even further implementing mechanisms such as monetary control. It explores such an alternative grid system that can develop alongside with the existing grid system but that also work without it. Because of its open architecture it can develop gradually, one subsystem at the time, thus requiring gradual investment. This is particularly interesting for areas that are currently off-grid. On a theoretical level, it provides an application model for open systems science in practice as well as explores the limitations of decentralization.

Acknowledgment

The authors would like to thank this research opportunity and the following participants for their essential contributions: A. André, H. Kitano, T. Morita, S. Tajima, M. Tokoro, and Y. Tokuda.

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