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A market-based smart grid approach to increasing power grid capacity without physical grid expansion

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Abstract The continuous increase of competitiveness of renewable energy in combination with the necessity of fossil fuel substitution leads to further electrification of the global energy system and therefore a need for large-scale power grid capacity increase. While physical grid expansion is not feasible for many countries, grid-driven energy management in the Smart Grid often interferes in customer processes and free access to the energy market. The paper solves this dilemma by proposing a market-based load schedule management approach that increases power grid capacity without physical grid expansion. This is achieved by allocating for a certain class of non-critical flexible loads called "conditional loads" the currently unused grid capacity dedicated to ensuring N − 1 security of supply whereas this security level remains untouched for all critical processes. The paper discusses the necessary processes and technical and operational requirements to operate such a system.

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1 Introduction

The continuous increase of competitiveness of renewable energy in combination with the necessity of fossil fuel substitution due to climate change leads to further electrification of the global energy system. Therefore, the capacity of the existing electricity grids needs to be upgraded substantially in order to meet the rising demand for electricity transportation and distribution. More specifically, on the electricity production side this is primarily due to new technologies like solar and wind penetrating the system. On the electricity demand side, so-called "conditional loads" like mobile and stationary batteries, power to heat applications and intersectoral technologies like power to gas drive the need for grid capacity extensions. The problem of grid congestions can be mitigated either by physical grid expansion or by a more efficient usage of the existing power grid capacity via IT-based energy management solutions in the Smart Grid. However, it is questionable if the high costs of assumed future large-scale grid expansion can be allocated to the grid user and grid-optimizing energy management solutions may intervene with the customer's energy consumption needs and restrict free access to the energy market based on grid constraints.

To solve this dilemma, the present paper proposes a novel approach to grid capacity increase without necessitating physical grid expansion. This is achieved by allocating for the conditional loads the currently unused grid capacity dedicated to ensuring N − 1 security of supply. While N − 1 security remains untouched for all critical ("unconditional") processes, conditional loads are temporarily shedded in the event of grid disturbance. This is possible, since they do not

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need the same security level due to their opportunistic operation behavior. A market-based incentive for the end customer to use conditional loads is given by a day-ahead load schedule management (LSM) for energy price optimization and a significantly lower grid fee for conditional loads. The incentive for the DSO is the possibility to postpone or avoid physical grid expansion at little additional costs.

The approach has been developed and prototypically implemented for medium voltage customers as part of the transnational research project "Power Alliance".[1] It will be field tested with DSOs and test customers from Germany and Switzerland in a follow-up project phase.

The remainder of this paper is organized as follows: Sect. 2 discusses related approaches, towards grid performance increase. In Sect. 3, we introduce the proposed approach and discuss its applicability in Sect. 4. A possible system architecture is sketched in Sect. 5 Finally, Sect. 6 summarizes the paper and gives an outlook to future work.

2 Related work

In the last few years, there have been many advances in the field of reducing or reallocating energy consumption with the goal to enhance grid performance and thus to reduce the need for grid expansion. This can be achieved using various concepts.

One option is to reduce peak demand. The most common way to do so is by applying load shifting and peak shaving techniques. This means that flexible loads are moved to non-peak hours [3,6,8,13,14]. This shift can either be done locally [14], but in most cases the DSO controlls it. However, this approach might lead to higher energy costs or reduced comfort for the end consumer because his energy market access as well as his free choice of energy consumption are restricted due to grid constraints. Another approach is to reduce the energy losses by sharing energy among customers [20], or to increase the overall energy efficiency by again using load shifting techniques [1]. As an example, the concept of energy sharing within microgrids is implemented in the project "Smart Operator" [15]. For all load shifting approaches, the grid capacity needs to be coordinated with the flexibilities, e.g. via a traffic light system. Advances in this area are the project "Grid Control" [19] and the cost-benefit analysis of a traffic light system in Switzerland [10] where the DSO directly controls the grid.

All the approaches discussed so far reduce the need for grid expansion, which is also the main objective of the project "Smart Grid Traffic Light Concept" [2]. However, these concepts might not be attractive from the customer's point of view. For a practicable way to enhance grid performance, it is important that both the end consumer as well as the DSO benefit from the solution.

Therefore, the reduction of peak demand, the support of grid stability, and hence the reduction of the need for grid expansion must be performed in line with either maintaining or reducing the energy costs and not harming the consumer's comfort level. There have already been attempts to combine some of these aspects. One possibility is to combine the grid-optimizing peak shaving approach described above with cost minimization for the end consumer [7,9,12,17]. Other ideas in this field are exploiting the optimization potential of household devices [11], introducing time-of-use tariffs [18], or simply maximizing the consumer's welfare under predefined grid constraints [16]. The present paper gives an alternative solution to this problem using a market-based approach. The advantage of the approach is that the consumer's flexible loads are used in such a way that a macroeconomic optimum between grid usage and energy market participation is achieved.

3 Increased grid capacity

We propose to solve the problem of increased grid utilization and risk of grid congestion by allocating for "conditional loads" the currently unused grid capacity reserved for the $N-1$ security of supply. In the following, we refer to this as the "increased grid capacity" (IGC) approach. Before elaborating on the IGC approach in Sect. 3.3, Sects. 3.1, 3.2 explain the $N-1$ criterion and provide definitions for the new terms "conditional" and "unconditional" load. Section 3.4 then shows how the IGC approach may be embedded in a business model by providing economic incentives to all stakeholders.

3.1 The $N-1$ criterion for security of supply

The $N-1$ criterion for security of supply is a rule according to which elements remaining in operation after failure of a single network element (such as a power line, a transformer or a generating unit), the system must be capable of accommodating the change of flows in the network caused by that single failure.

Figures 1, 2 illustrate the criterion exemplarily for the case of a power line outage in a simplified grid topology: Here, Fig. 1 shows a medium voltage grid section that is arranged as an open ring comprising two sub-circuits and an open switch. Figure 2 shows the same grid section in case of contingency with a power line outage in sub-circuit 2 that causes customers in sub-circuit 2 to be cut off from power supply. To rapidly restore power supply for these customers the switch is closed temporarily until the line outage is repaired. By closing the switch, the power flow is redirected via grid Sect. 1. By the $N-1$ criterion, the capacity of all affected power line

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[1] "Power Alliance - From local peak shaving to regional load shaping, a transnational demonstration initiative", ERA-Net Ref. No. 77601.

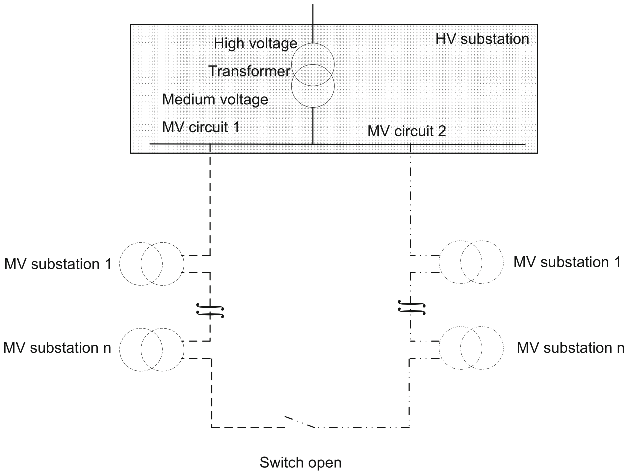

Fig. 1 Simplified medium voltage power grid topology

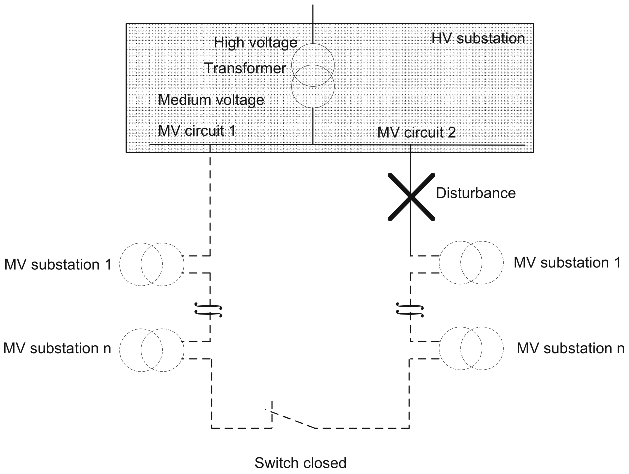

Fig. 2 Event of disturbance

segments must accommodate the resulting increased utilization. Particularly, in the depicted example topology, even the line segment with smallest capacity in sub-circuit 1 must hold available the additional capacity needed to accommodate the supply of all points of sub-circuit 2, and can thus be operated only at a fraction (e.g., 60%) of its capacity in normal operations.

3.2 Conditional and unconditional loads

We define *conditional loads* to be loads for which (1). N − 1 security is not essential, (2). that are highly price-sensitive, and (3). that are flexible and may therefore be used for price optimization purposes for the end consumer via dynamic load management (DLM). These loads comprise the charging of stationary batteries for internal consumption or power heat coupling for fuel substitution.

Unconditional loads are all other loads, i.e. they are 1. subject to the N − 1 criterion, 2. largely price-invariant (usually because energy costs are negligible in relation to operating costs), and 3. cannot be shifted flexibly in time. Unconditional loads typically include industrial production processes, supply of critical facilities such as hospitals, or household demand.

3.3 Increased grid capacity approach

With the increasing utilization of power lines, an increasing number of power line capacity bottlenecks occur. These bottlenecks exceed the N − 1 capacity threshold, forcing DSOs to either expand line capacity or to use energy management to automatically intervene in customers' load schedules in the event of congestion. While large-scale physical grid expansion is problematic for the national economy, top-down intervention in customers' load schedules is problematic from a customer's point of view, particularly for critical processes such as hospital supply or industrial production. To avoid this dilemma, we describe an automated energy management solution that 1. helps avoid large-scale physical grid expansion and 2. restricts top-down interventions to conditional loads.

By the N − 1 criterion, electricity grids are usually operated only at a fraction of their maximal capacity in normal operations. However, N − 1 security is by definition not essential for conditional loads and hence, the conventionally unused grid capacity may be dedicated to them without compromising the important security of supply level for conventional household and industrial loads.

To utilize this additional capacity, we implement a day-ahead LSM approach that intervenes with customers' conditional load schedules. To this end, all customers define their conditional load schedules on a day-ahead basis. To ensure that the total capacity for each grid sub-section is not exceeded, a traffic light system as proposed in [2] is installed with the following traffic light signal states: The traffic light signal is set to *green* as long as the sum of conditional and unconditional loads is below the maximal power capacity for each node. In this case, no interventions are necessary. The traffic light signal is set to *yellow* whenever the state of a grid sub-section is critical, i.e. whenever grid congestion occurs. In this case, the conditional loads are redistributed via DLM-based load shifting to ensure that the traffic light resumes to green. A *red* state would occur in case of grid congestion, which is not possible in this approach though.

To still ensure N − 1 security for unconditional loads in case of a grid disturbance, the DSO initiates load shedding of conditional loads before the switch is closed (see Sect. 3.1 for details). This is feasible without causing problems for customers due to the fact that by definition, conditional loads are not used for critical processes.

We call the combination between day-ahead load schedule management and real-time disturbance monitoring the *increased grid capacity* (IGC) approach. The IGC approach applies to all grid levels that implement N − 1 security, particularly the medium voltage grid.

Due to the assumption that the bulk of loads introduced to the energy system in the near future are conditional loads, while the increase of unconditional loads will be relatively small, the IGC approach is able to avoid large-scale grid congestion in the foreseeable future. Physical grid expansion will become necessary only for a relatively small number of power lines whose current capacity is already close to the N − 1 security threshold.

3.4 A business model for market-based grid control

We propose a business model that allows realizing a market-based approach to grid capacity increase according to the IGC approach. It is based on the assumption of a future liberalized energy market with increased price volatility, where energy management systems for price optimization of conventional flexibilities are already in place with most DSOs and grid customers. In this scenario, flexibilities are included in the calculation of the N − 1 criterion, causing an increased need for physical grid expansion.

To mitigate this effect, our proposed business model provides a market-based *incentive to grid customers* to register some of their flexibilities as conditional loads with the DSO. To this end, the DSO offers a new product for grid usage, which charges the customer with a radically lower grid fee for conditional loads than for conventional unconditional ones. We assume that the energy management system to operate the price sensitive conditional loads can easily be modified in terms of communication and load schedule handling to be used for DLM-based optimization of customers' conditional load schedules. Due to the assumed high price sensitivity of conditional loads, customers may gain significant economic advantage by conditional load optimization, particularly since corresponding conditional grid costs are negligible in relation to the assumed profit made in a volatile energy market.

The *incentives for the DSO* comprise the possibility to avoid comprehensive expansion of his distribution grid in the long run, while at the same time achieving a small increase of cash flow by additionally charged grid costs. Another incentive for the DSO to engage in a IGC solution is higher transparency within his grid because of customer side load measurement and DSO-registered load schedules.

4 Stakeholder adoption

In order to evaluate customer acceptance, to run model calculations and to field test the proposed IGC approach and business model, several use cases have been defined together with two DSOs involved in the Power Alliance research project. Here, grid sections with different characteristics (such as urban and suburban areas etc.) have been selected and test customers willing to participate in field tests for load optimization have been acquired. While the field tests, as well as the elaboration of concrete quantity structures and pricing schemes will be performed in a second project phase, interviews with the DSOs' management and with test customers have already been conducted in the first project phase to assess stakeholder adoption.

The survey results suggest the feasibility of the proposed business model. They show that the involved DSOs as well as a high percentage of grid customers agree on our generic assumptions regarding the development of the energy system and are willing to invest into an additional grid security product and energy price optimization of conditional loads. Yet, surveys also show that the decision highly depends on the relative difference between conditional and unconditional grid costs. If conditional grid costs are too close to the unconditional ones, grid customers strongly prefer the higher security level.

5 System architecture and workflow

In order to field test the proposed IGC approach in a subsequent project phase, a prototypical IT system has been implemented. In the following subsections, we briefly describe the high-level system architecture and the workflow for conditional load optimization.

5.1 The system architecture

The high-level system architecture of the IGC prototype is shown in Fig. 3. Here, the central management unit comprises two independent subsystems. By dividing the central management system into two separate subsystems, the system architecture complies with the ongoing liberalization of the energy market, which requires grid control and provision of energy supply to be operated by separate legal entities. The *Grid System* continuously monitors grid utilization based on the traffic light system, implementing automatic day-ahead LSM, i.e. it implements the grid perspective of capacity management. The *Energy System* collects the individually price-optimized load schedules of all connected customers, aggregates them, and, based on an iterative optimization process that interacts with the Grid System, ensures that the aggregated schedule does not violate grid capacity constraints, i.e. it implements the customer perspective of electricity price optimization. The inputs for the price optimization are provided by the *customer himself* (list of all devices) and the *energy traders* (electricity price). Connected to both management systems on the customer's side are on-site *Energy Managers* that control customers' devices.

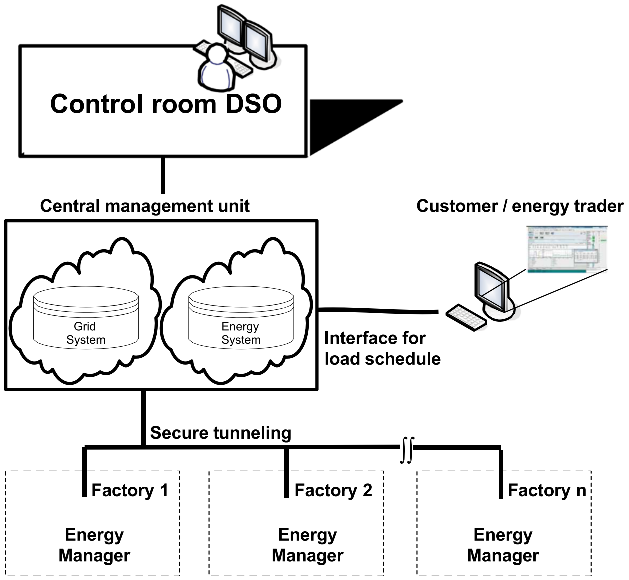

Fig. 3 The IGC high-level system architecture

The whole grid is supervised within the *DSO's control room* where all grid sub-sections are monitored simultaneously. The communication between the subsystems relies on a state-of-the-art security stack, including solutions for encryption, tunnelling, certificates and separation of duties and the overall architecture is designed to reduce any potential damage. The following subsections briefly elaborate on all system components.

5.1.1 Grid system

The Grid System is operated by either a DSO or a service provider. It (1) allows configuring and managing the grid topology, connected devices and connected consumers with their energy demands, and (2) automatically monitors grid utilization, visualizes the grid state in a dashboard, and prompts the Grid System operator to execute pertinent actions in grid substructures corresponding to the traffic light status.

The grid structure is stored in a relational database using closure tables [5], which allows easy and efficient querying of nodes and their children to support efficient load aggregation over substructures. For each node, the number of connected end customers as well as grid capacity constraints are stored. Grid System configuration and management can be accessed via a web interface, and the visualization component is implemented as a dashboard.

5.1.2 Energy system

The Energy System is operated by a service provider and/or the customer himself. It (1) allows configuring and managing devices of connected customers including device specifications, operating constraints and security of supply, and (2) automatically optimizes customers' individual load schedules according to energy price signals and operating constraints.

Representable device operating constraints comprise the min/mix amount of power the device can consume, the min/max amount of time the device should remain turned on and off, the min/max number of times the device should be turned on each day, the number of control stages the device can operate at, the necessary preparation time before the device can be turned on, the amount of cool down time before the device can be turned on again after shutting down, and dependencies with other devices.

5.1.3 Energy manager

The Energy Managers (1) automatically read information of connected devices, such as current operating state or charge condition, and (2) control these devices by, e.g. turning them on/off or limiting their power consumption. The Grid and Energy System interact with Energy Managers using a websocket connection, submitting a JSON-formatted command.

5.2 The workflow for day-ahead conditional load optimization

In order to provide an incentive for grid customers to participate in IGC grid capacity control, the IGC system provides customers with a mechanism to optimize their conditional load schedules according to price signals one day ahead. Since the central management unit is divided into two subsystems, load schedule management is set up as a time-based workflow that coordinates the interaction of the subsystems (cf. Fig. 4):

Step 1 Local Optimization: Based on (1) each customer's list of devices, (2) the corresponding device characteristics and operating constraints, and (3) energy price signals, the Energy System calculates a price-optimized conditional load schedule for every participating customer. Implementation is based on a binary device representation (1 = turned on, 0 = turned

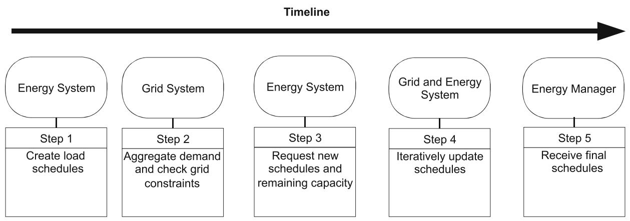

Fig. 4 Optimization workflow

off) and the NSGA-II genetic algorithm [4]. The Energy System then submits all individually optimized schedules to the Grid System.

Step 2 Global Optimization: The Grid System collects the individual load schedules and assigns to every traffic light node an aggregated load schedule that derives from the traffic light's position in the grid hierarchy. In case grid constraints are violated, it reduces or reassigns individual conditional loads. Here, schedule adaptations per customer depend on (1) the maximal amount of conditional load capacity of the subsystem in question and (2) on each customer's purchased conditional consumption boundary.

Step 3 The Energy System requests the adaptations of individual schedules from the Grid System, together with the remaining grid capacity at each time slot. Based on this information, each customer may submit a new schedule to the Grid System that complies with the capacity constraints.

Step 4 Steps 2–3 are reiterated until a predefined time-based deadline is reached. Each iteration step ends with a Global Optimization, so that the final state is guaranteed to comply with grid constraints.

Step 5 After the final deadline has been reached, the Energy System submits the consolidated schedules to the Energy Managers, which execute the schedules on the following day.

6 Conclusion and outlook

The paper discussed a novel approach to mitigating the effects of ongoing decarbonization to power grid utilization and the assumed resulting increased number of grid congestions. In contrast to most existing approaches, it minimizes the need for physical grid expansion while at the same time maximizing customer interests in terms of free market access and uninterrupted load scheduling for critical processes. This is achieved by allocating for so-called flexible and non-critical "conditional" loads the currently unused grid capacity dedicated to ensuring $N - 1$ security of supply. In case of contingency, these loads may be shedded without causing problems for energy consumers, thus allowing to utilize the complete existing grid capacity while maintaining $N-1$ security of supply for critical processes. To motivate customers to register conditional loads, the DSO offers a radically lower grid fee for conditional loads than for unconditional (critical) ones. Additionally, a DLM-based optimization module allows customers to optimize their conditional load schedules according to price signals. Interviews with stakeholders suggest that the proposed model finds acceptance with grid customers and DSOs and is applicable in practice. We also discuss the high-level system architecture of our prototype that complies with ongoing regulatory efforts to unbundling access.

In a second project phase, the real-time capacity monitoring system for load shedding, the intra-day load monitoring for the DSO dashboard, as well as a day-ahead prediction of each customer's unconditional loads will be implemented. The whole system will be field tested and iteratively fine-tuned with selected test- customers from Switzerland and Germany.

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