TOPOLOGICAL POWER PLANTS AS EMBEDDED MICROGRIDS FOR THE MARKET AND GRID INTEGRATION OF DISTRIBUTED ENERGY RESOURCES

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ABSTRACT

Coordinating flexibility from distributed energy resources (DER) poses a challenge as it becomes increasingly relevant for individual profitability and market integration as well as system and local needs (ancillary services). This paper introduces Topological Power Plants as a holistic integration approach for DER networks aiming at efficient market participation as well as at providing ancillary services. A distinguishing feature is the discussion of the approach by means of specific use cases in connection with corresponding role distributions. After outlining the concept, the developed modelling framework is described and preliminary results from field tests in southern Germany are evaluated.

INTRODUCTION

The goals associated with the energy transition will lead to an increasing share of distributed energy resources such as renewable energy sources and storage systems connected at distribution level [1]. Resulting challenges from market, system, local and individual perspectives require innovative solutions for the integration of DER [2, 3]. These challenges relate to the efficient use of the DER's flexibility for either trading purposes or for ancillary services as a potentially economic alternative to an exclusive grid expansion. Proposed concepts address individual flexibility use cases but generally lack a holistic consideration in connection with a respective role distribution [4, 5]. Against this background, this paper introduces Topological Power Plants (TPP) as a holistic integration approach for DER that regards both economic, system and local requirements. Based on the conceptual description and discussion of TPP, the implemented modelling framework as well as ongoing field tests are presented to demonstrate the technical feasibility and potential of TPP.

TOPOLOGICAL POWER PLANTS

Topological power plants are electrically coupled networks of DER and grid assets that provide ancillary services at a point of common coupling (PCC) for the overlaying or the neighbouring grid while complying with the restrictions of the local grid. The categorization of the TPP concept within existing integration approaches is hindered by a non-standardized collection of definitions falling under the generic term "smart grid". Smart grids can be described as comprising all developments associated with energy grids handling one-way flows of energy that evolve into pro-active grids dealing with multi-directional flows of energy and digital information [6]. A traditionally clear distinction between exclusively market- or grid-oriented approaches has been increasingly outweighed by combined concepts such as Technical Virtual Power Plants (TVPP) and microgrids [7–9]. However, the majority of the proposed holistic concepts either lack the level of specification (e.g. role distribution) and use case delimitation needed for implementation or the flexibility to be transferable to different regulatory and technical frameworks and requirements.

Use Cases

The main goal of TPP is to provide a coordination mechanism for the flexibility use at distribution level. As flexibility provision and demand are subject to case-specific conditions and requirements, the developed methods aim at providing a high degree of flexibility. For the purposes of this paper and of the field tests, the following use cases (UC) are considered:

- UC1: Participation in spot markets
- UC2: Provision of reserve energy for frequency control
- UC3: Compliance with active ($UC3_P$) and reactive ($UC3_Q$) power schedules at the PCC
- UC4: Provision of reactive power for voltage control and/or minimizing grid losses

While profit maximization and reserve energy provision are purely market-oriented goals for the DER operators and possible aggregators, the additional two use cases are system-oriented. Guaranteeing compliance with active power schedules helps improving grid operation and enables DER networks with predefined PCCs to contribute to redispatch carried out by Transmission System Operators (TSO). Current redispatch measures generally exclude DER due to an insufficient level of observability and controllability associated with these resources. The provision of reactive power can have benefits both for the local grid of the TPP (voltage control, loss minimization) and the overlaying grid (provision of capacitive or inductive reactive power). Previous works have mainly focussed on single use cases and mostly lack a combined scheduling and operation perspective [10, 11].

Role distribution

Depending on the market, technical and legal-regulatory frameworks, different role distributions are conceivable to implement the described use cases. An overview is given in Figure 1. Common to all role distribution options is the fact that the local DER network can be a subset of a nationwide Virtual Power Plant (VPP), which is generally more profitable than a geographically concentrated DER network. The provision of an active power schedule as well as pursuing its compliance at the PCC (UC1, UC2, $UC3_P$) can thereby be assigned to a regional agent of the VPP. The key differences between the possible role distributions relate to the provision of reactive power. The provision mechanism is currently determined by technical guidelines but with an increasing penetration of ICT at distribution level, further options are possible.

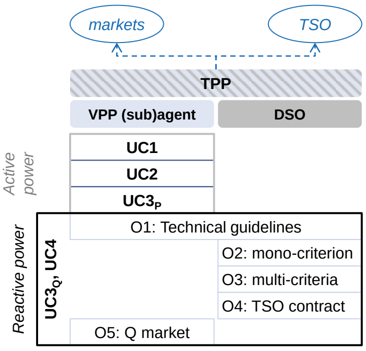

Figure 1: Use case-specific role distribution of TPP

In option 1 (Figure 1, O1) the current German regulatory framework is assumed, whereby DER are required to provide reactive power according to national technical guidelines instead of being subject to an innovative control strategy. The TPP is therefore limited to the operation and control of the DER network's active power feed-in in this option.

In options 2 (O2) and 3 (O3), the role of the TPP operator is split between the VPP subagent and the local DSO as the use of available data by one actor for both market and grid operation purposes is prohibited by the current liberalization-driven regulatory context in Europe. The DSO takes advantage of the DER network's existing ICT infrastructure in order to control its reactive power feed-in for grid-oriented purposes. In option 2 the DSO uses the TPP's reactive power for voltage control purposes at local level or for supporting the overlaying or neighbouring grid levels. In option 3 he additionally uses the TPP's reactive power for minimizing the local grid losses. In order to realize options 2 and 3, the DSO is bound to have sufficient information on its own grid (topology, generation and consumption) as well as extended power flow tools.

Option 4 (O4) comprises a contractual agreement between the TPP operator and the TSO of the overlaying grid. Hereby, the DER network provides a pre-agreed amount of reactive power at a specified PCC analogously to conventional power plants. As the TPP is connected to a distribution grid alongside other generation units and loads that are not necessarily part of the TPP, the contractual agreement must address their residual reactive power at the PCC. Depending on the level of knowledge over the grid situation required by the contract (e.g., if a forecast for the residual reactive power at the PCC is expected), the role of the TPP operator associated with the reactive power provision must again be assigned to the DSO in order to comply with unbundling requirements. First experiences with this option have been made by swissgrid [12].

In option 5 (O5) the TPP's reactive power provision is regulated by a market in which the DSO and/or TSO act as the demand side. Introducing such a market for reactive power entails the amendment of current and the establishment of new market and regulatory rulings. Despite the higher administrative overhead of this option, it can be arguably classified as the most transparent and non-discriminatory. In this option the position of the TPP operator would be hold by one agent only namely the VPP subagent.

MODELLING FRAMEWORK

For modelling the use cases and the role distribution of the TPP, different approaches were developed. The planning and complying process for the market-oriented schedules (UC1, UC2, $UC3_P$) is common to all available role distribution options and is based on a stochastic optimization programming approach. Taking pre-processed feed-in scenarios for renewable energy sources and price forecasts as well as technical and market restrictions into account, the optimal trading strategy at the spot and reserve energy markets is determined (see Figure 2 top two boxes). The obtained solution is an aggregated schedule for the DER network's aggregated power and is robust against weather forecast uncertainties to the extent regarded in the scenarios. The solution's validity for all scenarios is guaranteed by the portfolio's flexible assets such as storage systems, which compensate forecasting deviations in real-time. For the active power, the PCC of the TPP is not necessarily bound to a physical grid node as the compliance with the provided schedule is currently relevant for accounting reasons and thus only significant for the aggregated feed-in of possibly nationwide distributed DER.

For the grid-oriented scheduling process, there are two alternative modelling approaches. The combined scheduling approach envisages a linearization of grid restrictions (voltage and asset boundaries) and subsequent integration in the market-oriented optimization model. Therefore, it assumes a single entity for the TPP that has information on both market participation and grid states. The purpose of this approach is to provide insights into the TPP's theoretical potential when its contribution to market participation and grid operation is optimized simultaneously and thus with an overall consideration of the given restrictions and operational strategies. The respective modelling framework was developed in the context of the IREN2 project and a detailed description can be found in [11].

Sequential scheduling

For modelling the described use cases and role distribution, a sequential scheduling is a more suitable option. The corresponding modelling framework comprises an extended optimal power flow (OPF) module for verifying the compliance with grid restrictions and providing the reactive power schedules for the TPP's units in addition to the market-oriented scheduling (see Figure 2).

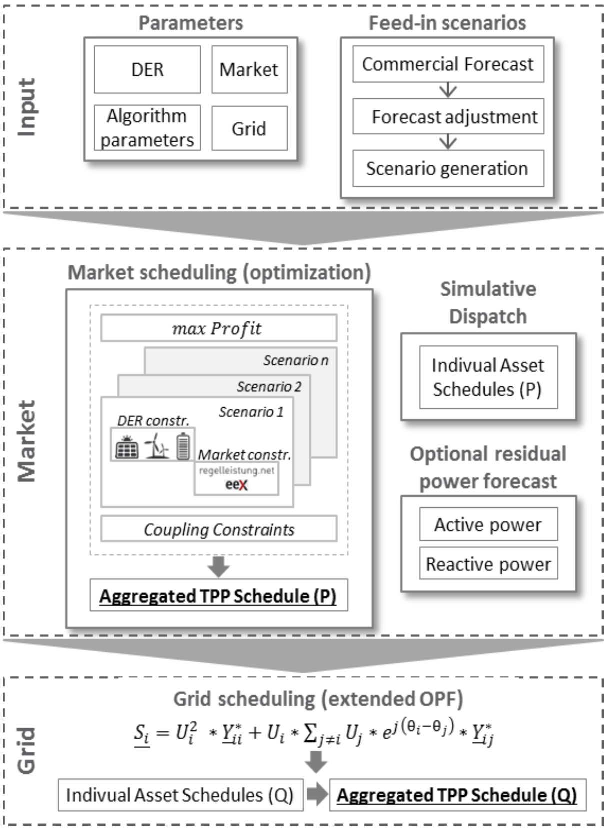

Figure 2: Modelling framework for TPP

The extended OPF is based on the Matpower simulation package [13]. It includes add-ons to enable power flow calculations across multiple voltage levels as well as a practical application of different operational strategies [14]. For the OPF calculations, the DSO needs a forecast for the expected power at every node, which includes an estimation of the demand, a forecast for generation units not included in the TPP as well as the unit-specific active power schedules of the TPP's DER. For this purpose, a simulative dispatch is carried out, which disaggregates the provided market schedule according to the expected values of the feed-in scenarios.

The operational strategies relate to the reactive power provision of the TPP at a pre-defined PCC and comprise the minimization, maximization or provision of reactive power within a pre-defined range. As TPP aim at providing ancillary services across voltage levels, the connecting node between two voltage levels (slack node between the low and medium voltage levels) offers a suitable PCC for the TPP's aggregated reactive power provision. As a consequence, the residual reactive power at the PCC must first be forecasted in order to determine the TPP's reactive power provision. Due to the stochastic nature of loads at distribution level and the nonlinearity of reactive power flows, artificial neural networks offer a practicable methodical approach for forecasting the residual reactive power at the slack node and were therefore chosen for implementation.

FIELD TESTS

The modelling framework for the sequential scheduling process of TPP was integrated into a real-time capable system connected to a control centre in Wildpoldsried, a small village in Southern Germany. The goal of the field tests is to demonstrate the technical feasibility and potential of TPP.

Design

For the field tests, the TPP was limited to a section of the LV grid. The TPP portfolio comprises five photovoltaic units amounting to 99.62 kWp, one 250 kW CHP unit and one 300 kVA, 162 kWh Lithium-Titanate storage unit. Furthermore, residential loads as well as a small business are connected to the regarded substation. A 500 kVA inverter station coupling the LV grid section with a separate MV grid is used during operation as a preservation measure for the assets as well as for ensuring an undistrubed security of supply during field tests in the LV grid.

The developed scheduling process is carried out daily after the new weather forecasts are uploaded at around 11 a.m. and provides a day-ahead schedule for the active and reactive power at the PCC. The PCC is located at the secondary substation. The calculated schedules thus combine on the one hand the TPP portfolio's spot market schedule with the forecasted residual load (active power at the PCC) and on the other hand the TPP's reactive power provision with the forecasted residual load (reactive power at the PCC).

A microgrid controller is located near a circuit breaker in the secondary substation and operates the controllable assets in real time. Deviations between the set points and the actual values are caused by both weather and residual load forecasting deviations and time resolution discrepancies. The schedules have a time resolution of 15 min in conformity with market requirements while the volatile behaviour of the loads and renewable energy sources have a much higher time resolution. The deviations are mainly compensated by the storage unit as a flexible asset.

Preliminary results

First field tests have been carried out according to the described setting. Figure 3 shows exemplary results for a day in late February. On the top graph, the market schedule for the TPP portfolio shows the relatively constant feed-in from the CHP unit at around 250 kW as well as the battery following the spot market signal. The charging occurs when the prices are low (around 4 a.m. and 11 p.m.). Due to the lack of solar irradiation on that day, a PV peak around midday is missing in the market schedule.

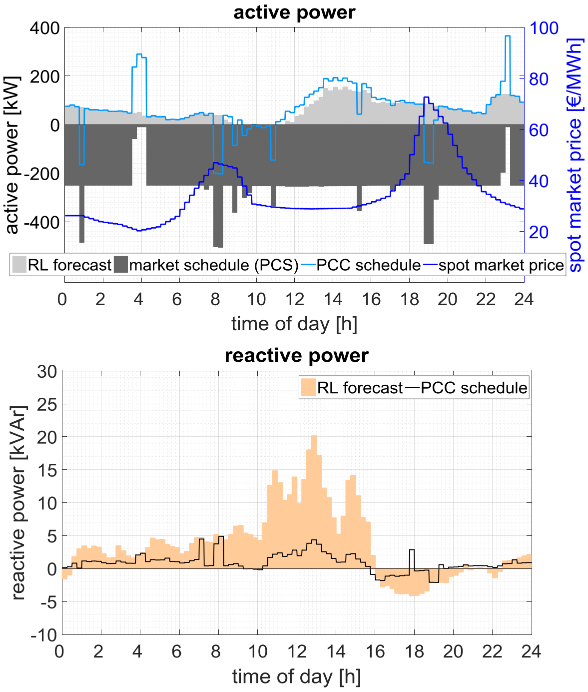

Figure 3: Preliminary field test results: active (top) and reactive power (bottom)

The bottom graph illustrates the TPP’s operational strategy. UC2 is assumed for the field tests, i.e. the reactive power exchange between the LV and MV grids is minimized. The reactive power’s potential of the sole controllable asset (battery) is determined during the scheduling process and, taking the forecasted residual reactive power at the PCC into account, used to minimize the reactive power exchange at the PCC. For the exemplary day, the reactive power exchange across voltage levels was reduced by around 69 %. Further field tests will provide further insight into the TPP’s potential for coordinating the flexibility at distribution level for both market- and grid-oriented purposes. The experiences gained in the field should provide a good basis for discussing the suitability of TPP as holistic integration concepts.

ACKNOWLEDGEMENTS

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

This research has been conducted in the context of the project “IREN2 - Zukunftsfähige Netze für die Integration Regenerativer Energiesysteme”. IREN2 is funded by the Federal Ministry of Economic Affairs and Energy within the funding initiative „Zukunftsfähige Stromnetze“. The partners are Siemens AG, AllgäuNetz GmbH & Co. KG, University of Applied Science Kempten and ID.KOM.

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