RESILIENT AND COMPREHENSIVE NETWORKS PLANNING IS KEY TO A SUCCESSFUL INTEGRATION OF RENEWABLE ENERGY RESOURCES

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ABSTRACT

The German "Energiewende" leads to significant uncertainty in terms of future demand and generation development. Distribution networks are mainly affected by the resulting different divergent requirements: Distribution networks are transformed into local transportation grids. Additionally network investments are restricted by regulation. The solution presented here combines strategic Asset Management (age & condition) and Network Development (capacity) in a synergetic fashion to raise significant technical & economical optimization potential. An adaption to uncertainty in the future is based on the analysis of a variety of load and feed-in scenarios. This approach enables optimal risk and cost aware decisions.

INTRODUCTION

Deregulation and large-scale generation from Distributed Energy Resources (DER) have increased the complexity for a cost-efficient power system planning. Grid operators are facing high uncertainties regarding investments in their asset base. These uncertainties are driven inter alia by an increased penetration of DER leading to an inversion of power flows within the network. Therefore classical Distribution Systems Operators (DSO's) are undergoing a transition to regional TSO's facing additional challenges: divergent and heterogeneous development scenarios, regulatory constraints and an asset base which is shifting to critical states due to under-investments in the context of the last years shrinking investment budgets.

The main idea has been developed in [1, 2] combining condition-based Asset Management (maintenance planning) and capacity based Network Development (expansion planning) in a synergetic fashion. The goal is to detect optimal investment strategies avoiding over-investments (stranded investments) and using the flexibility to adapt on the uncertain future requirements. The objective pursued is to find optimal new grid structures under different load and generation scenarios in terms of total costs (TOTEX) combining (N-1) contingency analysis, asset simulation and a hybrid evolutionary algorithm in a single system.

In [3] a prototype implementation has been introduced demonstrating that these synergies could be found in real distribution networks on 110kV level and lead to significant TOTEX savings. This paper presents the translation of the prototypical implementation into a DSO suitable planning tool.

OBJECTIVE

Which synergies should be identified by a Smart Planning system? Imagine a physical asset (e.g. transformer station, transformer, transmission line,…) which enters a critical state due to its aging in year t and must be exchanged as soon as possible in this state. Usually, this would be done by a replacement of an asset with equal or similar capacity. This investment would be regarded as stranded if DER generation or power demand affecting the specific asset in year $t+\Delta t$ (with $\Delta t \ll$ lifetime) exceeds the capacity of the resource. Smart Grid Planning should be able to identify such a situation for several generation and load scenarios simultaneously and should provide a grid configuration meeting the capacity constraints in year $t+\Delta t$ at optimal costs.

WORKFLOW

The synergy between Asset Strategy and Network Planning is identified in several steps:

1. Provision of long-term forecasts on a district resolution level over 15 years. The forecasts reflect the general expansion of renewable energy sources, the dismantling of conventional production and the demand as well.

2. Derivation of several Scenarios from the long-term forecasts and definition of Network Use Cases. The Scenarios and Use Cases define the future energy mix for PV, wind, biomass and demand.

3. A hotspot analysis gives insight into the behavior of the network currently installed taking the future projections defined by steps 1. and 2.: The analysis shows which assets receive critical states and/or exceed their capacity limits using power flow and asset simulation.

4. The financial model maps the asset base on financial measures including regulatory constraints. The measures which are determined by depreciations, CAPEX, OPEX and RevCaps.

5. An evolutionary memetic optimization technique is used to find a cost optimal solution which resolves critical asset conditions and capacity limits by network adaption. The memetic technique uses expert planning rules to reduce the complexity of the search space. The objective function is defined by the TOTEX and constraints are determined by age and capacity restrictions. The optimization uses The calculation of the objective function within the optimizer includes multiple simulation modules: a) Power flow analysis including (N-1) contingency analysis, b) State

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simulation of assets by forward projection of asset ages and c) Financial calculation under regulatory constraints.

6. A risk assessment is provided to the planner to select actions and their associated priorities. The need for action (probability weighted) can be derived from a Risk Matrix (probability vs. time horizon) directly. The selection gives an indication for the future TOTEX needed to develop the observed grid.

DESCRIPTION OF SYSTEM MODULES

Long-term forecasts & scenario definition

Based on macroeconomic global projections for long-energy consumption and production scenarios for energy mixes are derived: The scenarios are defined possible combinations of weak (μ–σ), average (μ) strong developments (μ+σ) for each renewable source and production as well. These combinations projected onto the planning period following the long-term forecast $LF_\mu(t)$.

Figure 1 shows scenario '1112' reflecting weak growth for consumption, wind and PV-production and average biomass generation. A probability P is assigned to each scenario where the sum of the probabilities over all scenarios results to 1.

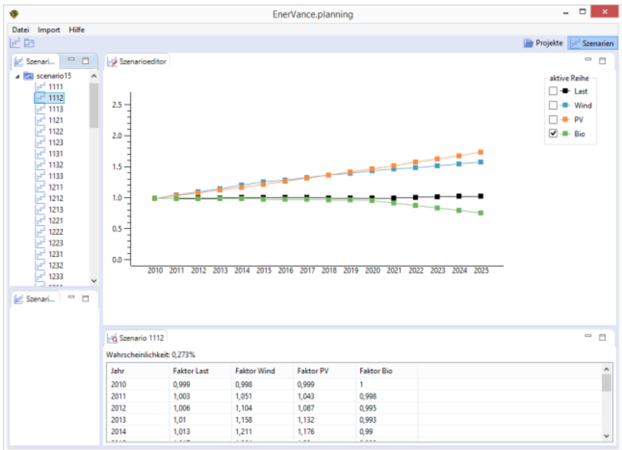

Figure 1: Scenario definition

Integrated simulation & Hotspot analysis

In a first step the actual asset base is assessed against all future scenarios and potential critical assets are identified by a Hotspot analysis.

Data Integration

Before an integrated Hotspot analysis including asset simulation and contingency analysis can be done network data have to be aligned. Since the network model and asset data are administered in different departments a mapping between data might be necessary. Figure 2 shows underground cables (dashed arrow and circle) with missing age information and their position in the grid diagram. The system allows to acquire the age and complement the model with this information.

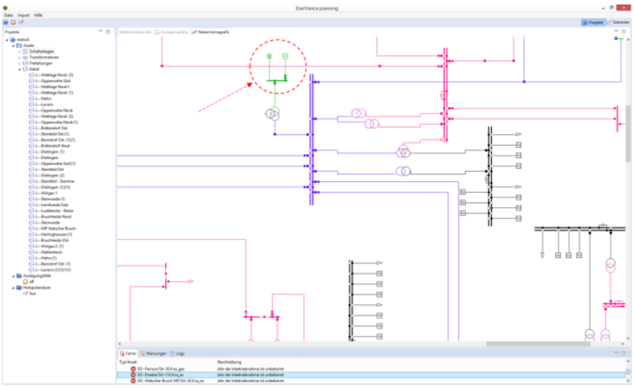

Figure 2: Data alignment

Power Flow Simulation

The grid under investigation entails a high complexity and level of detail in its technical description. To increase the significance of the planning approach, the grid has been reduced. For the power flow analysis, the grid is described by a network topology containing information about the electrical circuits representing the transmission lines (several segments build one circuit), transformers (including three winding transformers), switches, busbars and its bus-ties. The entire 110 kV grid is analyzed including the equipment of the 110, 30 and 10 kV voltage levels.

The network is assumed to be in the normal condition (N-0). This comprises a base setting of switches and bus-ties in the network configuration (open or closed). In order to perform a contingency analysis, the single outage conditions ((N-1) events) have to be determined. In a (N-1) case due to a failure of a single network element, two options have to be considered: If the network is separated into two disconnected parts (isolated networks), the grid must be merged again by switching actions. Switching actions close to the failure location restore the network structure. The appropriate actions are identified by a graph analysis algorithm before the contingency analysis is done. If the grid shows congestions in the (N-1) case there is the option of reducing the injected power generation. A first implementation includes a fix reduction of the power generation. A second approach foresees an optimal reduction pattern found by solving the following optimization problem: Minimize power generation constrained by the power line limits using power transfer distribution factors (PTDF) [4].

The power flow analysis is implemented in a DC Load flow model in Java.

- Nodal balance of installed generation and load (Scenario parameters)

- Network topologies of the (N-0) and (N-1) cases

Asset Simulation

The underlying asset simulation model works on each asset individually and is based on a bathtub curve shaped failure rate. The bathtub shape is defined using a piecewise defined function including the starting period with decreasing failure rates, a middle segment with constant failure rate and final segment with increasing failure rate of the underlying asset. Depending on the individual age of each asset the failure rate can be determined applying the bathtub curve. The cumulated potential failure rates define the 'criticalness' of the asset state which serves as an indicator for a replacement action.

Hotspot analysis

The Hotspot analysis summarizes all assets showing conditional (asset in a critical state) or functional (load exceeds capacity) triggers in a single view. Figure 3 depicts the list of affected assets (rows) and the trigger degree (diameter of the circles) over time (columns). The diameter in the capacity based case indicates the number of scenarios which lead to an overload. The Hotspot analysis gives a direct insight where actions are needed in the presence of the given scenarios.

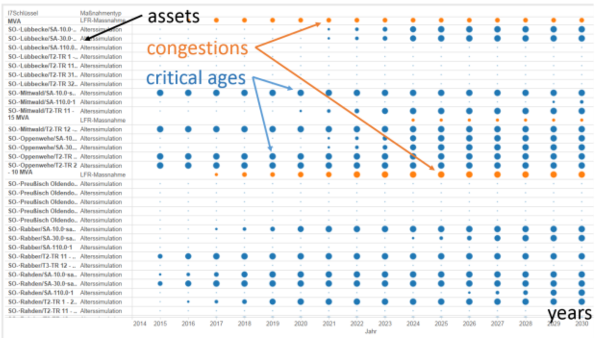

Figure 3: Hotspot analysis

Financial Model

As a result of an investment decision for each asset appropriate costs (or alternative KPIs) have to be provided for an optimization process. The objective function is based on the aggregation of all indicators (TOTEX or ROI). The TOTEX based objective function ignores regulatory effects whereas in the ROI approach regulatory effects on the revenue cap are included. The period of consideration is separated into the interval before regulation followed by the sequence of regulatory periods (each period is lasting five years).

Optimization Approach

The identification of synergetic actions which resolve critical asset states due to asset age and capacity restrictions defines the objective of optimization applied here.

In order to find feasible solutions despite the complexity of the underlying optimization problem additional knowledge could be incorporated. Domain experts are able to define a set of planning rules and to embed this information into an Evolutionary Algorithm used here. Literature refers to memetic algorithms or hybrid evolutionary computation if standard evolutionary algorithms are combined with heuristic rules for guiding the search process [5, 6]. Due to different options in combining standard evolutionary algorithms with heuristics there is a large variety of possible memetic approaches:

- Heuristics applied during initialization

- Application of "repair mechanisms" on the output from variation operators (also known as hybridization during genotype to phenotype mapping)

- Hybridization with the variation operators (crossover and/or mutation)

The algorithm applied here is based on a Genetic Algorithm due to the discrete nature of the underlying problem. The algorithm is extended by two kinds of hybridization: In order to find valid individuals during the variation process, DSO planning principles from experience are applied. On the other hand if a grid individual does not meet the capacity or state constraints for one or several scenarios it will be "repaired" and penalty costs are added to its objective function value.

RESULTS

The resulting planning solution offers the functional modules analysis, action and optimization. The module analysis supports workflow steps 1 to 3 providing the scenario definition and Hotspot analysis (see Figure 3), the module action enables the definition of a rule base for planning principles and the optimization module supports workflow steps 4 to 6 in form of the financial model, the evolutionary memetic optimization and the Risk Matrix (see Figure 5). The system is used to analyze and optimize two scenario sets and network asset bases.

Example Case I

First the system has been verified against a scenario where in a 60-node network section in year t_0=2013 an asset must be replaced due to its critical state (conditional trigger) while at $t_1=t_0+\Delta t$ the capacity of the new asset is exceeded in the given scenario as a result of the power flow calculation (functional trigger). Instead of adding an additional asset in year t_1 the optimizer should propose a well dimensioned asset already in year t_0 which satisfies the capacity constraints in year t_1.

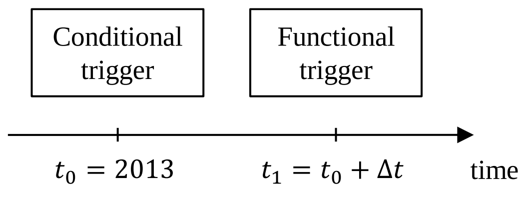

Figure 4: Investment triggers

Table 1 shows a solution for a model test case which is defined by 192 asset elements, a single scenario over 20 years of actions while the calculation of TOTEX is done over the entire depreciation period of 40 years. The unoptimized strategy shows the line segment between location **W** and location **R** which reaches its critical state due to its age in 2007 and must be replaced in 2013. This asset leads to a discounted TOTEX value of 2.271 TEUR. In 2013 the new line segment with identical capacity is build and depreciated over the next years until 2015 where a special amortization will be necessary since a functional trigger leads to a further capacity expansion in 2015. In contrast in the optimized strategy the replacement of the original line segment in 2013 already includes the additional capacity requirement in 2015. The comparison of the discounted TOTEX between both strategies shows a difference of 803 TEUR (=5.450 TEUR – 4.647 TEUR) identified by the optimizer.

Table 1: Optimization result

assets / TOTEX	discounted total	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
strategy wo synergy	TEUR										
segment/W-R	2.271	52									
segment/W-R/agebased	1.138							69	65	1.003	
segment/W-R/capacitybased	2.041									59	58
optimal strategy											
segment/W-R	2.271	52									
segment/W-R/opt-replace	2.376							71	68	67	66

Example Case II

In the second case a real 110kV sector with 600 nodes has been investigated. Figure 5 shows an exemplary asset (a transformer at location **M**) and the potential actions of the optimization run for a transformer in a Risk Matrix. The transformer station enters a critical state (conditional trigger) in 2015 and needs a capacity expansion (functional trigger) beginning in 2014.

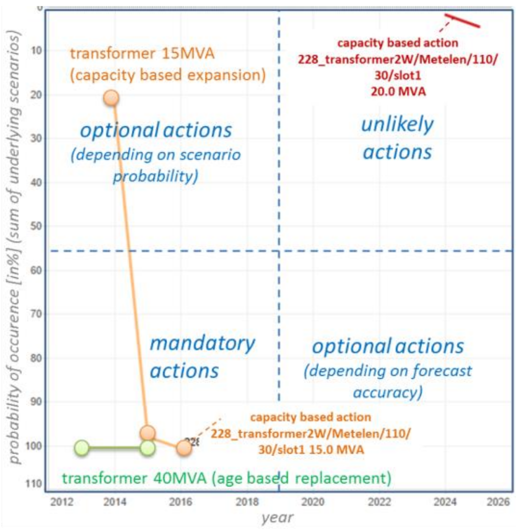

Figure 5: Transformer Risk Assessment

The need for a capacity expansion with additional 15 MVA starts in 2014 in a subset of scenarios with a cumulative probability of 20% (see y-axis), increases to 97% in 2015 and reaches 100% of the underlying scenarios in 2016. In 2024 further 20 MVA additional capacity for the **M** station is needed which reaches a scenario probability of 5% in 2025. The Risk Matrix serves as a decision base for the prioritization of actions: Actions in the lower left quadrant must be executed, actions in the upper right quadrant are unlikely to be applied. Actions in the upper left quadrant should be validated against the probability of the underlying scenarios while actions in the lower right quadrant must be assessed according to the quality of the long-term forecast. The Risk Matrix allows to balance investments and risks according in presence of uncertainty.

OUTLOOK

The system presented has been introduced as a decision support tool in the network planning process. An extension of interfaces e.g. to industry standard power flow tools is intended which simplifies the comparison of results.

The actual system assumes static intraday behavior of generation and production. An optional integration with agent based scenario generation is planned. The agents allow to model flexibility for example on the demand side or by means of storage.

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