LARGE SCALE AGENT BASED SIMULATION OF DISTRIBUTION GRID LOADING AND ITS PRACTICAL APPLICATION

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ABSTRACT

Academic studies and long-term planning demand for highly sophisticated simulation of distribution system's usage considering operational actions and repercussions of market driven measures when applied on a large scale. This paper presents enhancements to the SIMONA tool enabling a large-scale distribution system simulation of a lifelike 50,000 nodes model.

INTRODCUTION AND MOTIVATION

For efficient strategic energy system development, the long-term planning stage as well as academic studies try to anticipate the system's usage for periods of several years. Within this time horizon, new, yet unknown system usage patterns may arise. One of the most important steps in planning is to check, whether a given energy system is able to serve an assumed energy demand. Especially time-coupled assets, like storages or electric vehicles, do challenge conventional methods, such as static power flow calculations and require a time-series based assessment. A system is explicitly suitable when system operation staff is able to operate the foreseen system in real time without the system reaching a prohibited state. Therefore, the suitability-check shall be able to simulate operational actions as well. Moreover, the strategic assessment may also identify suitable incentive-based measures to reduce conventional grid reinforcement needs. Those measures may invoke unwanted and unintended independencies when applied to a large amount of entities. The agent based simulation environment *SIMONA* [1] is capable to fulfil all these requirements. Its modular bottom-up design allows for simulating grids of any theoretical size, while accounting for individual aims and strategies of single customers at the same time. The downside of this approach is a high computational effort and a huge amount of data.

Within the present paper, we will introduce relevant key features of *SIMONA* being mandatory for a large-scale simulation and afterwards apply it to a case study made with a real distribution grid model comprising approx. 50,000 nodes and nearly the same number of branches spanning five voltage levels.

RELEVANT SIMULATION FEATURES

Assessing the distribution system state of the aforementioned model for a period of one year in an hourly resolution means to calculate at least 438 million complex nodal powers – not accounted for iterative simulation of control schemes. *SIMONA* is a bottom-up simulation framework, determining each single nodal power based on the individual behaviour of all approx. 20,000 connected assets. This gives some impression of the computational effort raised by such a case study. In the following some insight into simulation features needed, to handle such a comprehensive distribution grid model and its arising computational complexity are depicted.

Tap-changing three winding transformers

Higher voltage levels often comprise special and complex assets. One of those assets is a three winding transformer. Whilst tap changers may occur on high or low voltage side of two winding transformers, with three windings, it can only be apparent on the high voltage side.

Based on [2] the authors model a three winding transformer as an adopted T-one-line diagram shown in **Figure 1**. The virtual node does belong to voltage level A whilst the admittances $\underline{Y}'_{\mathrm{SC,B}}$ and $\underline{Y}'_{\mathrm{SC,C}}$ are referred to voltage level A as denoted by the apostrophe. One main design aspect of *SIMONA* is to assign galvanically separated subnets to distinct *NetAgent*s justified by the advantage, that the simulation of different subnets can be dispersed on different computers, as the used JADE framework allows message delivery along physically networks. The different voltage levels are connected via messages sent during a forward backward sweep through the levels. The lowest levels do a power flow calculation and do sent their apparent power exchanged via the interconnection nodes to the higher voltage levels until the highest level is reached. That subnet then sends the calculated nodal voltages at the interconnection nodes to its lower grids, which recalculates the power flow, so that it also can forward its nodal voltages. This is done back and forth until exchanged power values do not change anymore between the iterations.

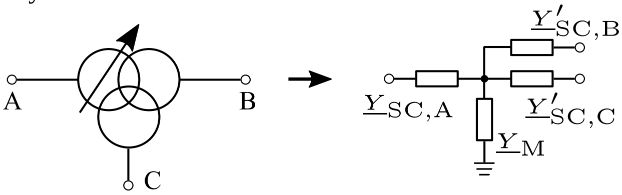

Figure 1: Circuit symbol and equivalent one-line diagram of a tap-changing three winding transformer

For two winding transformers this process is quite simple, as by design we choose to regard for them in the lower voltage level. With three winding transformers, it becomes more complicated, as the exchanged power has to be handled at the virtual node. Therefore, we split up the equivalent circuit and disperse it to the three concerned *NetAgent*s as shown in **Figure 2**. Following the above-mentioned forward backward sweep, *NetAgent* B and C first announce their apparent residual power via message (1). If there is a voltage measurement assigned to the given transformer in one of the inferior subnets, the respective *NetAgent* also attaches a voltage regulation request Δv with its favoured in- or decrease in nodal voltage at the connecting node. *NetAgent* A does receive the messages, adds the apparent powers up and assigns them as node apparent power for later power flow calculation. Additionally, it balances the received voltage regulation requests and adjusts the tap changer accordingly. When the forward backward sweep is on its backward part, *NetAgent* A sends the newly calculated nodal voltage as well as the chosen tap changer position to its inferior *NetAgent*s B and C via message (2).

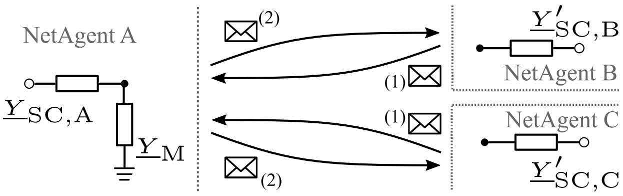

Figure 2: Message transfer between different NetAgents

Although the subnets A, B and C are strongly coupled in a triangular interacting dependency, the above presented approach allows for easy parallelisation of grid simulation and thereby enables simulations of large-scale grids.

Multiple slack nodes

In addition to having three winding transformers in high voltage grids, it is also common to have meshed grid structure fed at more than one node from extra high voltage level. Having in mind, that *SIMONA* divides the total grid model up into galvanically decoupled grid models, multiple coupling points to superior levels impose the need to model multiple slack nodes per grid.

By default, the used Newton Raphson (NR) power flow algorithm does not allow for having multiple slack nodes. To overcome this shortcoming, we introduce a *SlackEmulator* model. One node is arbitrarily chosen as the "real" slack node, whereas the others serve as connecting point for the previously mentioned *SlackEmulator*s. Those are dummy elements providing or consuming a fixed nodal apparent power and storing the target voltage of its connecting node.

We establish an additional loop around the NR calculation: For the first iteration, the nodal residual powers are summed up to estimate the total subnets residual power, that later has to be balanced by the available slack nodes. We evenly assign this apparent residual power to all slack nodes – better to say available *SlackEmulator*s – of this subnet. Given a valid power flow result, the actual residual power is recalculated and once again dispersed to all *SlackEmulator*s. The additional loop ends, when the change in all *SlackEmulator*s is less than a pre-set threshold. During the backward stage of the power flow algorithm, the given *NetAgent* receives the calculated nodal voltage at each coupling point from its superior *NetAgent*. In order to account for this recalculated nodal voltage, all nodes serving as emulated slack nodes are modeled as PV nodes having the received voltage magnitude as target voltage.

In this way, the total subnets' residual power is evenly divided up to all coupling points. For future development an impedance weighted balancing is intended to use to allow for an even more detailed calculation, when the coupling points differ much in their impedance-based distance to the total grid model's slack node.

Simple continuous power flow calculation

In *SIMONA* the power flow calculation is realised as a numeric NR calculation. Based on an initial guess of the nodal voltages describing the system's state, non-linear system equations are solved, until the system state converges. The grid usage defines different classes of challenges to the NR algorithm [3]. The proposed approach addresses performance improvements for well-conditioned power flow problems as well as leveraging the risk of not finding a solution based on ill-conditioned problems with small regions of attraction [3]. Until now various complex methods have been developed to improve performance of power flow calculation [4]. Anyhow, the authors intend to make use of the special application properties, time series based power flow calculation proposes to the classic NR algorithm: Time series based distribution system assessment is to simulate continuous system usage. Hence, we assume, that a) the system is not changing drastically over each time step and b) the usage pattern will also not change too much. Therefore, we use the last known information about the system to make a better starting guess for the NR calculation of the next time step.

The nodal residual apparent powers $\underline{\boldsymbol{S}}_{\mathrm{N}}$ and Kirchhoff's law describe the system state – by the nodal voltages $\underline{\boldsymbol{V}}_{\mathrm{N}}$ – as a system of non-linear equations:

$$\underline{\boldsymbol{S}}_{\mathrm{N}} = \underline{\boldsymbol{V}}_{\mathrm{N}} \circ \underline{\boldsymbol{I}}_{\mathrm{N}}^{*} = \underline{\boldsymbol{V}}_{\mathrm{N}} \circ \left([\boldsymbol{Y}_{\mathrm{N}}] \cdot \underline{\boldsymbol{V}}_{\mathrm{N}}\right)^{*} \tag{1}$$

In equation (1) the nodal admittance matrix is denoted as $[\boldsymbol{Y}_{\mathrm{N}}]$ and $\circ$ describes the Hadamard product – the element wise product of each vector. The NR algorithm is an iterative approach and its basic principle is to linearize the quadratic system equations in each k^{th} iteration step by means of a multi-dimensional Taylor transformation and applying the corrections to the solution of the previous iteration step $(k-1)$:

$$\begin{pmatrix} \boldsymbol{f}^{(k)} \\ \boldsymbol{e}^{(k)} \end{pmatrix} = \begin{pmatrix} \boldsymbol{f}^{(k-1)} \\ \boldsymbol{e}^{(k-1)} \end{pmatrix} + \begin{pmatrix} \Delta\boldsymbol{f}^{(k)} \\ \Delta\boldsymbol{e}^{(k)} \end{pmatrix} \tag{2}$$

with

$$\underbrace{\begin{bmatrix} \frac{\partial P}{\partial f} & \frac{\partial P}{\partial e} \\ \frac{\partial Q}{\partial f} & \frac{\partial Q}{\partial e} \\ \frac{\partial V^2}{\partial f} & \frac{\partial V^2}{\partial e} \end{bmatrix}^{(k)}}_{[\underline{\boldsymbol{J}}_{\mathrm{N}}]^{(k)}} \cdot \begin{pmatrix} \Delta\boldsymbol{f}^{(k)} \\ \Delta\boldsymbol{e}^{(k)} \end{pmatrix} = \begin{pmatrix} \Delta\boldsymbol{P}^{(k)} \\ \Delta\boldsymbol{Q}^{(k)} \\ \Delta\boldsymbol{V^2}^{(k)} \end{pmatrix} \tag{3}$$

$$\Leftrightarrow \begin{pmatrix} \Delta\boldsymbol{f}^{(k)} \\ \Delta\boldsymbol{e}^{(k)} \end{pmatrix} = [\underline{\boldsymbol{J}}_{\mathrm{N}}]^{(k)^{-1}} \cdot \begin{pmatrix} \Delta\boldsymbol{P}^{(k)} \\ \Delta\boldsymbol{Q}^{(k)} \\ \Delta\boldsymbol{V^2}^{(k)} \end{pmatrix} \tag{4}$$

Equations (2)-(4) comprise the current iteration step k, the jacobian matrix $[\underline{\boldsymbol{J}}_{\mathrm{N}}]^{(k)}$ of this iteration step, the node voltage corrections $\Delta\boldsymbol{e}^{(k)}$ resp. $\Delta\boldsymbol{f}^{(k)}$ and the vector of changes in active power ($\Delta\boldsymbol{P}^{(k)}$), reactive power ($\Delta\boldsymbol{Q}^{(k)}$) for each PQ node as well as the change in squared voltage magnitude ($\Delta\boldsymbol{V^2}^{(k)}$) in each PV node in comparison to the previous iteration step $(k-1)$.

Given the aforementioned assumption, that both the grid structure as well as the grid usage – described by the vector of nodal apparent powers – are not expected to differ much from time step $(t-1)$ to t, the last known Jacobian matrix $[\underline{\boldsymbol{J}}_{\mathrm{N}}]_{t-1}^{(k)}$ may help in making a good estimation for the start vector in t

$$\begin{pmatrix} \boldsymbol{f}^{(0)} \\ \boldsymbol{e}^{(0)} \end{pmatrix}_t = [\underline{\boldsymbol{J}}_{\mathrm{N}}]_{t-1}^{(k)^{-1}} \cdot \begin{pmatrix} \boldsymbol{P}_t^{(0)} - \boldsymbol{P}_{t-1}^{(k)} \\ \boldsymbol{Q}_t^{(0)} - \boldsymbol{Q}_{t-1}^{(k)} \\ \boldsymbol{V^2}_t^{(0)} - \boldsymbol{V^2}_{t-1}^{(0)} \end{pmatrix} \tag{5}$$

by the help of the known nodal powers in time step $(t-1)$ lying satisfactorily close to the final result, reducing the amount of iterations. Although a single iteration does not take a long time, each saved iteration highly increases the scalability of the simulation due to the high number of power flow calculations.

Wide area voltage regulation

Time series based distribution grid simulation reduces the disparity of planning process to operation simulation, as the operative measures or control schemes should favourably be accounted for in planning as well. One interesting aspect in this context is the simulation of transformer tap control schemes.

In general, there are two schemes used in practical application. Local transformer tap control simply compares the voltage magnitude at the transformer's secondary bus to a pre-set threshold. On the other hand, wide area control scheme accounts for measurements submitted by voltage measurements installed at nodes prone to extremal voltage magnitudes.

To account for this, we introduce measurement system models to *SIMONA*. They may be placed at some nodes in the grid and define a restriction on what simulation values may be available to a given control scheme. Within the simulation's configuration stage, the user is able to define a trigger model – comprising minimum and maximum voltage magnitude threshold as well as a list of available measurement systems – and assign it to the given transformers, both two and three winding.

By the help of those measurement system, *SIMONA* is capable to simulate both local and wide area tap control schemes, examine the impact of different measurement placing strategies and may develop further control schemes based on the availability of measurements in the grid under testing.

RESULT PRESENTATION

The outcome of such a large-scale simulation is a huge amount of data, which needs to be presented and analysed appropriately. In conformance with the Gartner definition, large-scale simulation is regarded as part of Big Data [5]. Big Data analysis requires an extensive data access when joining different data sources. Usually this includes full table scans over the entire data volume, which define expensive database operations. Here the authors follow a Deep Data approach, which takes the data gathered and pairs it with industry experts who have in-depth knowledge of the area. Deep Data pares down the massive amount of information into useful sections, excluding redundancy. Instead of just thinking "big" when it comes to data, the approach is to start thinking "deep". The Deep Data framework is based on the premise that a small number of information-rich data sources, when leveraged properly, can yield greater value than vast volumes of data [6],[7]. The approach starts with the definition of appropriate granularity levels derived from business use cases of grid planning or asset management using methods like the Kimball Enterprise-Bus-Matrix [8]. The identification of coarser granularity allows for pre-aggregated data representations and smaller data volumes. The Kimball matrix is used to derive the information-rich data sources as an efficient foundation of further analysis.

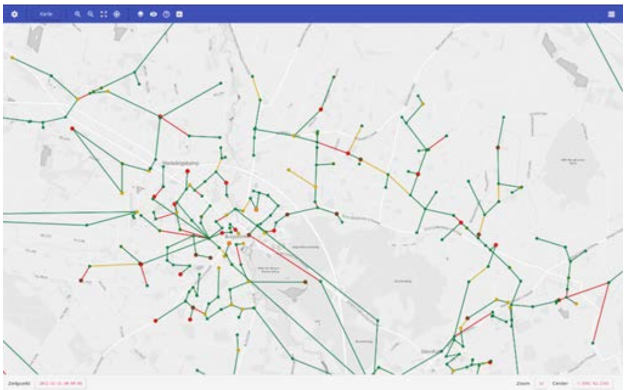

Figure 3: Visualisation of Key Performance Values

The proposed approach includes the preparation of measures like asset loading, voltage magnitude and angle in geospatial, schematic and tabular views. These views can be controlled by rich filter functions restricting the key performance values to dedicated dimension elements like scenarios, time intervals, regions or voltage levels on aggregated and detailed levels. **Figure 3** shows the aggregated asset loading as the selected key performance indicator in a mid-voltage grid sector.

CASE STUDY

To demonstrate the presented concept, we carry out a case study. Please notice, that it has not been focus yet to find a good system state by trimming the model parameters, but to show the large scale applicability of our agent-based simulation environment *SIMONA*.

Simulation model

A lifelike distribution grid model of the project Agent.GridPlan [9] has been used in this paper. It comprises two medium voltage (MV) levels and each one extra high (EHV), high (HV) and low voltage (LV) level with the key values listed in Table 1.

Table 1: Key values of the simulation model

Volt. lvl.	Subnets	Nodes	Branches	Shunts
5	568	47,661	47,814	20,403

The shunt elements represent both assets for consuming and producing energy. Loads are modelled as standard household loads as per German standard load profile [10]. All generating assets are modelled following a bottom-up approach, calculating the apparent power output based on (non-)electrical fundamental data [1]. Simulations are carried out with weather data for one day in July with an hourly resolution. As the correct geographical siting of nodes is known, all weather dependent assets are served with the geographically correct weather data.

Investigation A: Performance increase with simple continuous power flow

The first investigation targets the potential performance increase using the aforementioned approach of guessing improved start vectors for power flow calculation in comparison to simply using the target voltages. A PC with Intel Xeon E5-1650 CPU and 128 GB RAM serves as simulation platform.

The total simulation times shown in Table 2 reveal that the improved guessing of start vectors can be reduced by approx. 0.98 % depending on the actual simulation. In order to determine the final distribution grid state of one subnet in each time step, a lot of power flow calculations have to be carried out. Iteration loops are introduced by

- the forward backward sweep to integrate all voltage levels,
- balancing out the subnets residual power on different slack nodes and
- control schemes (like $Q(V)$ control and traffic light concept [11]) or negotiations

among others. Therefore, if one of four to six inner iterations can be saved, this has a major impact on the overall performance.

Table 2: Total simulation time for both calculation approaches

	Simple	Extended
Simulation time	640.79 s	629.68 s
+ Export time	1,140.82 s	1,180.10 s

Moreover, the comparison between simulation with or without result export highlights the urgency to think about further usage of simulation results. Persisting everything costs around 180 % to 190 % of total time. Although using buffers and parallelisation decouples actual simulation and Input/Output-processes, further steps could only take place, when all results are available in database. Therefore, the following remarks should be considered when applying time series based simulations on a larger scale:

1) The (needed) output of the simulation shall be specified properly. Data filtering and information compression shall be used where possible and loss-free in terms of information – Deep Data instead of Big Data as already mentioned.
2) Integration of processes and tools plays a major role. When data can be kept in memory and directly handed over to next process steps, major savings can be made. Therefore, increased discussion about open interface definitions and open source tools is appropriate.

How iteratively interacting process modules and information compression could be realised, was also part of the Agent.GridPlan project and can be reviewed in [12].

Investigation B: Wide area monitoring system

As a simple realistic application example, we conduct a comparative assessment of using local vs. wide area tap control scheme.

The permissible voltage dead band of ± 10 % [13] at each end customer's connection point has been assigned with ± 4 % to MV level and ± 6 % LV level comprising also the voltage drop over the secondary substation transformer as usually applied in German distribution grid studies [14]. To determine the transformer trigger settings, two initial simulations are made with the following settings: Transformers have a fixed tap position that would lead to a secondary bus voltage close to $1.03\,\mathrm{p.u.}$. The first simulation A is ran with only load to determine each subnet i's maximum voltage drop $\Delta v_{\mathrm{drop,max},i}$. Analogously for high infeed and low load (30 %) to determine $\Delta v_{\mathrm{rise,max},i}$ (simulation B). To ensure compliance with voltage thresholds the triggers are set to:

$$v_{\mathrm{trig,incr},i} = 0.96\,\mathrm{p.u.} + \left|\Delta v_{\mathrm{drop,max},i}\right| \qquad (6)$$

$$v_{\mathrm{trig,decr},i} = 1.04\,\mathrm{p.u.} - \left|\Delta v_{\mathrm{rise,max},i}\right| \qquad (7)$$

Additionally simulation A and B define the candidates for voltage measurements used in wide area control scheme (simulation C) as the nodes with the extremal voltages. The triggers for simulation C are set to:

$$v_{\text{trig,incr},i} = 0.96\ \text{p.u.} + \Delta v_{\text{Tap}} \quad (8)$$

$$v_{\text{trig,decr},i} = 1.04\ \text{p.u.} - \Delta v_{\text{Tap}} \quad (9)$$

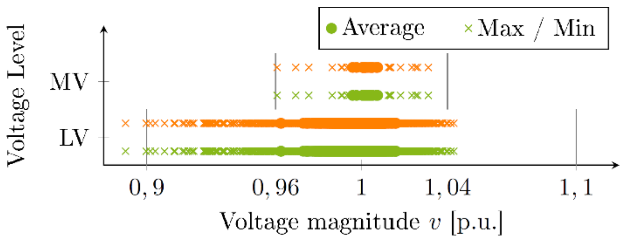

Figure 4: Nodal voltages in both control schemes (green: local control, orange: wide area control)

Figure 4 shows, that local tap control is not able to prohibit violations in LV, whereas no violation in MV is apparent. Moreover, also the wide are control scheme is not able to relieve the violations in LV. Obviously the assumed voltage limits per voltage level are not suitable and need to be revised. This highlights *SIMONA*s potential in assisting planning engineers in their decision-making.

CONCLUSION AND OUTLOOK

The present paper gives insight into simulation (model) complexity arising, when time series based grid performance assessment shall be used. With the shown adoptions *SIMONA* proofs to be a powerful tool to be used for academic studies, like [12] and for use in long term planning processes.

Future work will mostly focus on how time series based grid performance assessment can be incorporated in easy to use and comprehensive future-ready planning processes. Main topics of interest are reduction of data, recognition of repeating usage patterns as well as decision supportive functionalities.

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