Time series based distribution grid planning approach with decentralised voltage regulation

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Abstract— One of the most crucial constraints in operation of power systems is keeping the permitted voltage intervals. Uncontrolled distributed generation may cause voltage problems in distribution grids, due to static power factors. Recent converter technologies allow variation of the power factor. Therefore, the consideration of units with these technologies in the planning process respects their ability of providing reactive power. Then, unnecessary network extension can be avoided.

In this paper, an extension of an agent-based simulation platform for distribution networks is presented. The decentralized generation units are represented by agents that are able to adjust the reactive power consumption or in-feed according to the network status. In combination with the voltage control the presented system provides realistic loading and voltage time series for a selected grid section. With this simulation the utilities are able to determine the probability of loading situations and plan their network in a more efficient way.

Keywords: distribution network planning, time-series, voltage regulation, agent-based simulation, renewable energy sources

I. INTRODUCTION

Recent German studies show, that the necessity for electric distribution grid extension in the low and medium voltage layer is mainly driven by voltage boundary violations [1]. Distributed generation units (DGU) are historically operated a static power factor equal to one, so no reactive power is provided or consumed. Meanwhile, the converter equipment of new units is able to be operated with power factors that can be adapted to the actual situation. However, utilities usually use static power factors in distribution grid planning, without covering the converter capabilities completely. Due to the coupling between reactive power feed-in and the network voltage profile, the controllability of distributed generation as well as a static variance of the power factor should be considered in the planning process to reduce the required network extension.

The authors of [2][3][4][5] also state, that voltage control mechanisms should be taken into account in the grid planning process. It is suggested to implement voltage-depending reactive feed-in control (Q(U)-voltage control) capabilities for DGU when the number of installed units rises significantly. Today, these control schemes can be considered in the conventional network planning process, where only extreme scenarios (feed-back-case, load-case) are taken into account, via adjusting the constant factors of DGU. This downside remains for the probabilistic network planning approach where the probability of occurrence of scenarios can be evaluated [6] but complex controls and negotiations are difficult to model.

To improve these problems this work implements the suggested control mechanisms in an existing multi agent system for grid planning purposes and enables the evaluation of these controls on a time series base. With the multi agent system, complex interactions and reactions can be modelled, since every single network participant is represented by an agent. These participants, like loads, storage systems or renewable energy sources, can implement different objective functions, like market or network oriented behaviour. Even demand side management reactions of industry loads or private households can be modelled. Although increasing the complexity of the network planning process, this can augment the efficiency of network asset usage. In conjunction with analysis methods for time series like median duration curves, the network planner gets a new toolset to decrease the operation reserve of the system and therefore raise the usage efficiency.

The paper is structured in five sections. First the general structure of the multi agent system and the embedding of the voltage regulating distributed generation units are presented. Afterwards, multiple voltage control schemes and their integration in the system are described. The paper concludes with the scenario evaluation in a small low voltage network and the result discussion.

II. MULTI AGENT SYSTEM

The multi agent system (MAS) first presented in [7] was developed to generate time series for distribution grid loads. One of the main benefits of this approach is the possibility to break down the complex interactions between network participants ([8]) like demand side management or voltage regulation negotiations of distributed renewable generation units (DGU).

In this section the general proceeding of the implemented system is described. The developed MAS represents every network participant of the distribution grid as a single agent as shown in Fig. 1.
After the initialisation phase, in which the agents are set up with their individual simulation parameters, the time agent sends all agents the simulation time step (see (1) in Fig. 1).

The DGU and load agents receive the corresponding weather information from the nearest weather agents and the node agents pass the time step information to the connected DGU and loads (2). Additionally, the market agent provides the current market price. With this information the DGU agents calculate their output values according to [7], [9] and [10]. The resulting in-feed and load is sent to the node agent, representing the network connection point (3).

Every node agent sends the complex nodal power to the grid agent (4) which performs an AC load flow calculation representative for measurements in the system. Since the system allows for complex negotiations in dependency of the network loading status or the local market price, the market and grid agent detect if the system reaches steady state and inform the time agent to start a new time step (5).

A. Modelling of the load agent

The main focus in this paper is the demonstration of the voltage regulation mechanism in distribution grids. Therefore, the loads in the systems are modelled as reactive agents that derive their behaviour only based on the day time. They implement a standard load profile characteristic for households [11], which is scaled by an assumed yearly energy consumption. The corresponding reactive power consumption is calculated with constant $\cos \phi = 0.95$.

B. Modelling of the grid agent

Based on the nodal active and reactive power balances, which are provided by the node agents, the grid agent performs a complex load flow calculation. Since the DGU agents are not able to determine the local complex voltage profile, the grid agents sends all relevant system data to the DGU agents for voltage regulation purposes or any other measuring data dependent unit in the distribution grid. The decentralised concept of MAS [8] is not violated by this rather centralised aspect, because the grid agent does not control the other agents but just provides necessary information.

C. Modelling of DGU units

With a very high installed capacity of photovoltaic and wind energy units in the German distribution grid, it is mandatory to consider existing units and annexe in the network planning process. Therefore every distributed renewable generation unit is represented by a DGU agent in the MAS. The nominal power and location is published in [12] and available for all units. Unit specific parameters e.g. the azimuth and horizontal orientation as well as inverter type are either also available for the simulated region or estimated based on typical values for units in the database. [9][10]

Every single agent request the required weather information for a simulation time step from multiple weather agents located nearby. Weather agents represent a node of a 7 km by 7 km grid. The represented information is calculated by the COSMO-EU weather model of German Meteorological Service (DWD). [13]

III. Voltage control schemes integration in the MAS

Apart from the load and feed-in balance the voltage stability and control is a major issue in electric distribution grids. Recent studies [1] show, that voltage violations are a major cause for network extensions in the standard scenario based network planning process. In this chapter two decentralized approaches are presented. On the one hand the common local control schemes for DGU and on the other hand a coordinated approach with a controlling node agent for multiple units connected to one grid connection point.

Since the network losses scale with the line-current and therefore with the additional reactive power transfer, it is reasonable to reduce the additional reactive power feed-in to a minimum. In the past, connecting DGU with a constant $\cos \phi = 1$ was a common practice. Due to the increased amount of installed capacity of DGU and the raising voltage problems, most of the grid connection guidelines now require either a constant $\cos \phi \neq 1$, a local $\cos \phi (P)$- or a local $Q(U)$-control for the units to be allowed to connect to the grid. In Germany, these guidelines are usually based on general technical guidelines [14] and [15]. In addition to these reactive power control concepts, where only local data is necessary, a centralised voltage control concept is proposed. In difference to the others, the grid agent sets the nodal voltages to target values and inquires the DGU agents of the necessary reactive power. In the following all occurrences of an inductive $\cos \phi$ implicate, that the DGU consumes reactive power.

To evaluate all approaches by means of time series the control mechanisms are implemented in the MAS and the integration is described in the following section.

A. Voltage control based on the active power in-feed

A major downside of a constant $\cos \phi$ for a DGU is the higher median of losses for the unit. For this reason a local control via $\cos \phi (P)$ is demanded by many DSO. Since the active power in-feed of DGU increases the voltage in the grid, the reactive power consumption is controlled with a characteristic depicted in Fig. 2 to counteract this effect. In the medium voltage grid (10-30 kV) all units have to provide a local $\cos \phi (P)$ control. In contrast, the DGU in the low voltage grid are requested to be operated with a fixed $\cos \phi = 0.95_{\text{cap}}$ or $\cos \phi = 0.95_{\text{ind}}$, depending on the connecting site. If a unit has a nominal power $S_{DGU,n} > 3.68 kVA$ [14] this...
unit has to provide $\cos \phi (P)$-control with a limit of $\cos \phi = 0.95\text{ind}$. For units $S_{DGU,n} > 13.8 \text{kVA}$ the limit is increased to $\cos \phi = 0.9\text{ind}$.\textsuperscript{[14]}

For the implementation of the $\cos \phi (P)$ in the agent system every DGU-agent calculates its reactive power $Q_{DGU}$ considering the given characteristic (see Fig. 2) and active power feed-in $P_{DGU}$ according to the weather situation. The interaction with the residual MAS is explained with Fig. 3. The results of the calculation of the DGU-agents are sent to the node agent (1), and, combined with the load data, forwarded to the grid agent (2). In the following, the grid agent performs a load-flow calculation with all nodal powers (3). Afterwards, when the calculation is completed, the grid agent informs the time agent and stores the calculation results into an external database (4).

Another method for regulating the reactive power in-feed is in functional correlation to the voltage at the grid connection point of the DGU with $Q_{DGU} = f(U)$. Depending on the characteristic, the DGU could provide reactive power in high load times to support the voltage profile of the network. One major downside of this method is the possible necessity of control characteristic adaptation when the network topology changes or the installed DGU capacity increases. Therefore the operation expenditures of such a system may be higher in comparison to the $\cos \phi (P)$-control.

A generalized control characteristic for DGU is suggested in\textsuperscript{[16]} and depicted in Fig. 4. It is essentially a standard $Q(U)$-control characteristic with a symmetric dead band for $U = U_{\text{set}} \pm \text{lim}$. With the maximal reactive power consumption $Q_{\text{max}}$ in coherence with the nodal voltage $U$, the suggested control neglects the effect of individual adjustments of the network, but reduces the network losses.

Since this control characteristic makes $Q_{DGU}$ dependent of the voltage $U$, the implementation of arbitrary $Q(U)$-voltage control characteristics in the MAS requires a cyclic behaviour according to Fig. 5.
With the network voltage profile being dependent on the nodal reactive power in-feed, the communication steps 1-5 are executed until the network status reaches a steady state. The results are written to a database afterwards (6). The adjustment of $Q_{DGU}$ is done in parallel for all DGU units in the network.

Since the grid agent performs a load flow calculation this feasible approach can be improved if the grid agent calculates the reactive power requirements for every node in the grid. With this approach the feed-in units at every node negotiate the necessary reactive power feed-in. A node agent is representing the grid connection point of the DGU in low voltage grid (building connection) or in the medium / high voltage layer a grid connection point for multiple units. The negotiation process of the coordinated voltage regulation is shown in Fig. 6.

![Diagram showing the process of reactive power negotiation](image)

Fig. 6. Loadflow based Q(U)-control implementation in the MAS

At this point the steps (1) – sending time stamp - and (2) - forwarding time stamp and sending weather data - of the overall MAS (Fig. 1) are completed.

The DGU agents send the active power $P_{DGU}$ and reactive power $Q_{DGU}$, which have been calculated with the weather data input to the corresponding node agent (1). Additionally to the other method, they inform the node agent about their controllability $\xi$. In this first step, the reactive power $Q_{1,DGU}$ is set to zero by every full controllable unit, thus generating the base case for the optimization. All non-controllable DGU behave according to their local control characteristics. Being normally a PQ node during the simulation, the nodes with controllable DGU are set to PV nodes. The node agent aggregates the received information to the nodal powers $P_{node}$ and $Q_{node}$ and sent them together with the node type (PQ or PF) to the grid agent (2). The grid agent calculates a complex load-flow to determine if a violation of the accepted voltage interval $\pm \Delta U$ occurs in the system (3). If a voltage violation is detected, the voltage setpoint for this node $i$ is redefined with the set point voltage at the transformer $U_{TF,N}$ according to:

$$U_{i,\text{set}} = U_{TF,N} + \Delta U$$

With this new setpoint and the adapted node types, i.e. nodes with the controllable units set to PV, the load flow is recalculated to determine the necessary reactive power $Q_{set}$ for every controllable node to reach the requested $U_{i,\text{set}}$ (4). This amount of reactive power is send to the corresponding node agent (5), which is redistributing the requested reactive power to the connected controllable units (6). The requested amount for each DGU is depending on its nominal power. If a single unit cannot provide the requested amount of reactive power, it responds with a refuse message, containing its maximum reactive power capability and final output ($P_{fin,DGU}, Q_{fin,DGU}$) (7). The sum of active $P_{fin,\text{node}}$ and the negotiated sum of reactive power $Q_{fin,\text{node}}$ are sent to the grid agent in step (8). This process is executed simultaneously for every node with voltage violation and group of DGU in the system.

The final step is the load flow calculation with the negotiated reactive power values. All nodes are now considered as PQ type. The resulting final voltage profile $\bar{U}_{fin}$ and the nodal power vectors $\bar{P}_{fin}, \bar{Q}_{fin}$ are written to a database for further analysis of the time series. Additionally the time agent is informed that the negotiation process is completed and continuation with the next system time step is possible.

**IV. SIMULATION**

**A. The simulation test environment**

For the demonstration of the simulation system and the different voltage control approaches an exemplary low voltage grid is constructed. The system is also applicable in the medium or high voltage layer but the simplicity of low voltage feeders is beneficial for the evaluation.

The test grid parameters are based on the research results of [17] and [18] to develop a representative low voltage grid model. It consists of a medium/low voltage substation with four low voltage feeders (F1 – F4), shown in Fig. 7.

![Diagram showing the test environment](image)

Fig. 7. Test environment

In this work the analysis focuses on the cable feeder F3 that powers a typical residential area in Germany. The cable of feeder F3 has a diameter of 150 mm² throughout the whole line. The feeder connects 32 households to the overlaying grid with distances between the households varying between 18 and 32 m. The length of the first section is extended to 150 m. Photovoltaic generators with rated installed capacity of 10 kW are installed at three nodes in F3. The transformer has a rated
capacity of 400 kVA and the voltage at the medium voltage bus bar is set to 1 pu. Since the photovoltaic generators are assumed to be installed under outdated grid connection guidelines, they are all operated with $\cos \varphi = 1$. The residual feeders are not considered in detail and therefore represented by a compensatory load and photovoltaic generator as presented in Fig. 7.

The DGU agents in the MAS require geographically referenced weather data. For this purpose the test network is located in North-Western Germany. The historic weather information is derived from European weather simulation model COSMO-EU of the German Meteorological Service (DWD). [13] The simulated time period includes 358 h and starts on the 1st of May 2011. This particular time frame was chosen because of a very high direct and diffuse radiation in the test area. For a clear presentation the active power simulation results for a 30 kW unit are sorted and depicted in Fig. 8. If the test system was placed in another region or the simulated time frame was adjusted it would not increase the amplitude of the maximal values but the frequency of occurrence of the maximal active power output. In only nine time steps of the test period an active power output of 21 kW is exceeded. Therefore a scaling factor of $P_{DSU} = 0.7$ is suitable to compare the time series results to the static planning approach.

![Fig. 8. Sorted active power time series for a DGU with $P_{n} = 30 \text{kVA}$](image)

### B. Scenarios

To evaluate the implementation of the specified reactive power controlling mechanisms, four scenarios are defined. For all scenarios two units with a nominal power of 30 kVA are installed in the feeder F3 at position 27 and 32 (see Fig. 7). The load-agents provide a standard load profile characteristic which is scaled by the typical German average annual energy consumption. The corresponding reactive power consumption is calculated with a $\cos \varphi = 0.95$. With these assumptions, the four scenarios are set up as:

- **Base Scenario**: The additional 30 kW-units are not connected to F3
- **Scenario A**: All DGU in the system operate with $\cos \varphi = 1$.
- **Scenario B**: All DGU in the system are operated with $\cos \varphi = 1$, except the DGU at node F3_32, which is operated with a $\cos \varphi (P)$-control and an under-excited limit of $\cos \varphi_{min} = 0.9$ ind.
- **Scenario C**: All DGU in the system are operated with $\cos \varphi = 1$, the DGU at node F3_32 is operated with a $Q(U)$-control and an under-excited limit of $\cos \varphi_{min} = 0.9$ ind.
- **Scenario D**: All DGU in F3 are operated with a $\cos \varphi (P)$-control and a limit of $\cos \varphi_{min} = 0.9$ ind.

In the following, the scenarios are evaluated from a standard network planning standpoint as reference for the time series based approach. While the high-load case was the dominating dimensioning scenario for distribution grids in the past, today’s common practise is using two dimensioning scenarios for the network. Due to the massive integration of new DGU, the case of low load and high renewable feed-in becomes the main reason for network extension in distribution grids [1]. The assumed parameters for the conventional analysis are:

- feed-in case:
  \[
  P_{DGU,i} = 0.7 \cdot P_{DGU,i \forall \text{DGU}}
  \]
  \[
  P_{load,i} = 0.1 \cdot P_{load,i \forall \text{loads}}
  \]

- high load case:
  \[
  P_{DGU,i} = 0 \forall \text{DGU}
  \]
  \[
  P_{load,i} = P_{load,i \forall \text{loads}}
  \]

If the feed-in case is evaluated in the conventional static analysis, the nodal voltage at the end of F3 is 1.01 pu in the base scenario without the two requested photovoltaic generators. Analysing Scenario A, the voltage of the last base scenario without the two requested photovoltaic generators. Analysing Scenario A, the voltage of the last base scenario without the two requested photovoltaic generators. Analysing Scenario A, the voltage rise is reduced to 1.045 pu. There are very minor differences between the two Scenarios due to the

<table>
<thead>
<tr>
<th>Table 1: Results of the conventional scenario based planning process for the defined scenarios</th>
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<tr>
<td>$U_{F3,\text{end}}$ [pu]</td>
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<tr>
<td>Base Scenario</td>
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<tr>
<td>Scenario A</td>
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<td>Scenario B</td>
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<td>Scenario C</td>
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<td>Scenario B’</td>
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<td>Scenario D</td>
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With the reactive power control set according to scenario B and C, the voltage rise is reduced to 1.045 pu. There are very minor differences between the two scenarios due to the
different reactive power limits with the scaled active power feed-in. Even if the second DGU at connection node F3_27 is also equipped with reactive power control defined in Scenario B, the $U_{\text{F3, end}}$ can be only be lowered to 1.041 pu (Scenario B’). The consent of the connection request would only be possible in combination with grid extension. Only in Scenario D, where additionally all existing units are retrofitted with reactive power controlling capabilities, the two requested units can be connected without violating planning and operation rules.

C. Results

In the following section time series simulations are carried out for all scenarios with the implementation of $\cos \varphi (P)$-control for Scenario B and D as well as the power-flow based $Q(U)$-control for Scenario C.

It can be stated, that the analogue the conventional approach, network assets are not thermally overloaded. In Fig. 9 the percentage line utilization is depicted. In coherence to the static network planning process (results in Table 1), asset utilization does not result in network extension in any scenario. The line loading never exceeds 25% even for high in-feed periods in Scenario A to C. A $\cos \varphi (P)$-control for all DGU in the feeder (Scenario D) results increases the line loading by 5% for 1/8 of the total simulation time. Therefore the influence of the different controlling approaches on the asset loading can be neglected.

![Duration curve of the related line loading time series for the first segment of F3](image)

Evaluating the results of the voltage time series depicted in Fig. 10, the upper voltage boundary (1.04 pu) is only violated in 20 hours within the simulated time period in Scenario A.

If the DGU at node F3_32 is $\cos \varphi (P)$-controlled (scenario B), the voltage violation occurrence can be reduced to 7 hours. With this rare possibility of occurrence the DSO may evaluate the option to limit the power feed for the additional 30 kW DGU in these time steps and spare the network extension in the feeder.

If the DSO encourages the DGU owner to implement a local $Q(U)$-control, voltage boundary violations can be eliminated completely. Because the control in Scenario C directly reacts on the overvoltage at the node the DGU only consumes reactive power when necessary. Therefore the network is operated at the voltage limit for more time steps but the total network losses and inverter losses are reduced because no excess reactive power is consumed. The configuration of Scenario D, which is the most intricate but the only option to connect the new DGU from a static network planning perspective, is not necessary. The nodal voltage at the end of strand F3 is significantly reduced below the voltage boundary for the critical time steps in the simulated period. This additional, excess reactive power transfer to the DGU induces additional network losses and inverter losses for the DGU operator and should be avoided.

With this information in mind, the Scenario B may become a valid connection option for the DSO if the DGU operator also agrees to a remote limitation of the DGU in-feed in very rare cases. With the avoided network extension costs, the DGU operator could be compensated for the infeed limitation for many years. Additionally the time series simulations have shown that scenario C cannot be correctly evaluated with standard network planning methods. The time dependent influence of the load is not correctly considered with the low scaling factor of 0.1. Scenario D is the only valid option for the connection of two additional 30 kW units in the test system from a standard network planning perspective apart from network extension. However, the time series analysis of this scenario depicts, that this operation configuration is overdimensioned for the purpose. The retrofitting of all DGU in the feeder would invoke additional costs in comparison to scenario B with remote power limitation.

![Duration curve subset of the $U_{\text{F3, 32}}$ time series](image)

V. CONCLUSION

An agent based system was developed, modelling interdependencies of network participants in the distribution grid to improve the planner’s base of decisions. In this work, the multi agent system is complemented with reactive power control capability for decentralized generation units with inverter feed-in of arbitrary types. Therefore three controlling methods and their integration in the multi agent system are described. The influence of control strategies on the network loading and voltage profile is demonstrated in an exemplary low voltage test grid.
Via modelling the control capabilities of distributed generation, the network planner can evaluate these in conjunction with the time series of all network participants. In comparison to the extreme scenario based planning approach, the interaction and interdependencies of all network participants can result in an optimised asset utilization and voltage profile of the investigated region.

A subsequent analysis of the generated time series allows for a probabilistic network planning process with the opportunity to evaluate, if direct control limitations of distributed generation are more economic than conventional network extension. Even in the long-term view, such options can be more economical than a conventional network extension, if the probability of the overloading or voltage boundary violation scenario is low.

Since the utilities are commended to increase the efficiency of their distribution grid by the government, one possibility is the decrease of infrastructure’s total costs. The time series based approach can provide the required data basis. The main advantage of the multi agent system over standard time series for the planning process remains the option to model the interdependencies of negotiation processes on the participants. This can be future power flow controlling approaches or virtual distributed storages or even market based congestion control algorithms.

In future work the authors will implement demand side management functions for loads as well as a market based supply side management for decentralized in-feed. Innovative network extension options like controllable local grid transformers or network oriented storage systems will be implemented as well. Facing future developments, electric vehicles with individual mobility and charging behaviours will be implemented in the next steps. Since the voltage layer of the distribution- and transmission-grid are strongly coupled the exchange between the sub-systems will be taken into account accordingly and therefore enable multi-layer simulation and planning of whole distribution grid regions in the future.

REFERENCES