Agent Based Coordination Mechanisms for Grid Serving Control of Charging Stations

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***Abstract*—This contribution presents two different grid serving coordination mechanisms for the control of charging stations based on a multi agent approach. In the first coordination mechanism the agents control autonomously and in the second coordination mechanism the agents create a collaborative controls strategy by negotiation and interaction. In addition, the structure of the multi agent system is discussed and the control modelling of a charging station is described. Finally, the stability of the control mechanisms are critically analysed.**

Keywords—Multi agent, distribution grid, grid serving control, charging station control

I. Challenges of the German Energy Transisition

In order to reduce carbon dioxide emissions by local climate protection objectives, many municipalities are relying on increased electrification of the transport sector by electric cars based on renewable energies [1, p. 15]. For a distribution grid operator (DSO), the implementation of the electrification of transport manifests itself in the increasing integration of public and private charging station infrastructures. In the past, no distribution network was planned to meet new challenges. Cable overloads or voltage boundary violations are consequences of this progress. In addition to the distribution grid problems, data protection issues also arise with regard to the billing of energy consumption by an electric car owner. The transitional provision §48 of the measuring point operating act simplifies temporarily data protection requirements so that DSOs can install measuring systems at charging stations to record energy consumptions [2, p. 25]. According to [3, p. 68], the control of charging stations can be optimised by providing complete user information on mobility requirements and using it for grid serving aspects. In the law on the digitalisation of the energy system transformation and the measuring point operating act it is noticeable that data protection is given high priority. For this reason, the DSO is unlikely to host or possess all user information centrally. In order to counteract these problems, the multi agent approach paradigm is used. This approach allows the development of software agents which can be deployed decentrally over several industrial personal computers (PC) in the distribution grid. These software agents are located in the vicinity of the charging stations and are able to control the charging stations. Therefore, the software agents are called actuator agents. These actuator agents host all user information in a decentralized manner and comply with data protection guidelines. This paper consists of six sections. In addition to the introduction in section I, section II deals with the structure of the agent based grid automation system. Section III introduces two different coordination mechanisms for the control of charging stations. In section IV, the control model of the charging station is presented and in section V, the coordination mechanisms are critically analysed. Finally, section VI summarizes the results.

II. Agent Based Grid Automation

For the implementation of an agent based grid automation system (GAS), it is necessary to install different types of assets like sensors, industrial PCs, communication infrastructures and actuators. In the agent based system, software agents with different tasks and objectives are deployed on PCs, to control the corresponding assets [4, p.2].

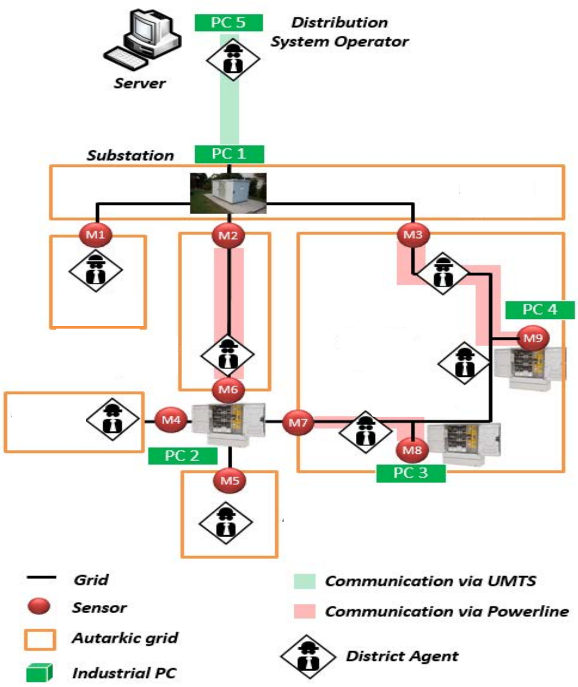

Figure 1: Hardware structure of a multi-agent system [4, p.2]

Figure 1 shows the structure of the agent based GAS, which is installed in a real low voltage distribution grid. As shown in this figure the distribution grid is divided into six districts. Each district is bounded by one or more sensors and is able to independently determine the grid state based on the measurements of these sensors (depicted in red). Thus, the districts are called autarkic grids in the sense of the grid state detection. The sensors are located either in cable cabinets or in transformer substations and at the charging stations. Additionally, industrial PCs are installed in these locations to host the software agents. For communication within the GAS and to the DSO, different technologies, like Powerline, Ethernet or UMTS are used. The software agents are configured and tested by the DSO on its server. Afterwards they are remotely deployed to the industrial PCs in the field [5]. These software agents can then determine the grid state of their corresponding autarkic grids. In the case of critical grid states, each agent can autonomously make control decisions based on its own actuators. For this reason, these software agents are called "District Agents".

III. AGENT BASED CONTROL MECHANISMS

A key requirement for GAS is the reduction of communication effort and the possibility of island operation in the event of a technical failure. Decentralised evaluation of the actual grid state and decentralised finding of a suitable control strategy reduces the communication effort. For this purpose, each charging station must be equipped with an autonomous controller as shown in the figure below.

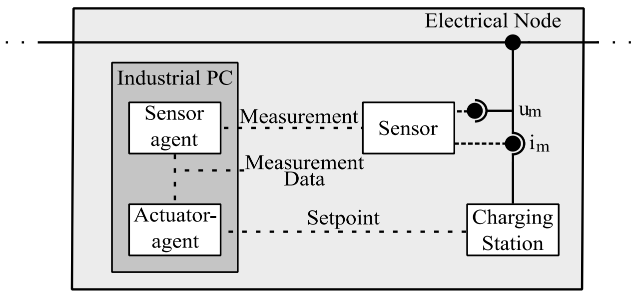

Figure 2: Configuration of an autonomous controller

The sensor agent receives a measurement from the sensor and forwards the processed measurement information to the actuator agent. In the event of a voltage band violation, the actuator agent sends a setpoint to the actuator, which the actuator then executes to correct the critical grid state. This control mechanism is an autonomous control mechanism. The autonomous controller is only able to detect local voltage band violations at the node, which are corrected by the actuator of the autonomous controller. The autonomous controller is not sufficient for the detection and control of cable overloads and non-local voltage band violations. In addition, the actuator agent of the charging station only measures the local node and does not know the grid state of the entire distribution grid. But the superordinate District agent is able to determine the entire grid state and is the initiator for a coordinated control. The District agent is only a coordination agent and has no direct influence on the actuators. Furthermore, the District agent does not know the control model of the charging station. However, the actuator agent knows the detailed control model of his assigned actuator, so that a control strategy can be found via an interactive control mechanism. The following sections describe the autonomous and interactively coordinated control mechanisms.

A. *Autonomous Control Mechanism*

The autonomous control concept is used to eliminate local voltage band violations at the node of the actuator. This control unit should work autonomously without communication and interaction with other software agents and should have a simplified knowledge about the influence of its control decision. The recommended method is the control by a characteristic curve, which is already established in the control of generators [6, p. 1]. Here, voltage-dependent characteristic curves are given to the autonomous controller or the executing software agent for adapting the power at the actuator.

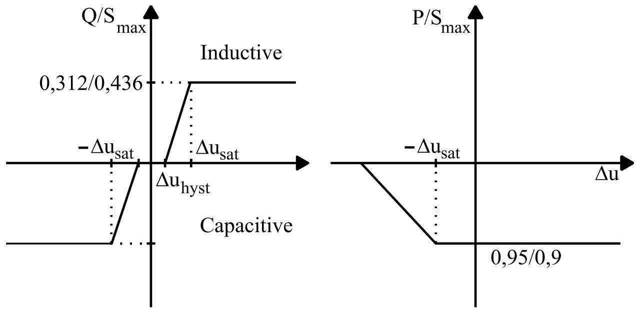

Figure 3:Autonomous, voltage dependent control of charging stations

Figure 3 illustrates the autonomous, voltage-dependent control of charging stations. The left diagram shows the characteristic curve for the $Q(\Delta u)$ control and the right diagram shows the characteristic curve for the $P(\Delta u)$ control, where Δu is defined by the deviation between the current u_{act} and the rated voltage u_n. The measured nodal voltage at the actuator can contain measurement errors. But the controller should not be activated on basis of the measurement errors. The control is activated until the hysteresis value Δu_{hyst} is exceeded. Below the hysteresis value Δu_{hyst} there is only a small need for control, which may not exist at all due to the measurement error. If the voltage deviation Δu is greater than the hysteresis value Δu_{hyst}, the reactive power is changed proportionally to the voltage deviation Δu. The reactive power at the actuator can be varied up to a maximum reactive power saturation value $Q_{sat} = 0{,}312, 0{,}436 \cdot S_{max}$ and will remain constant if the saturation voltage deviation value Δu_{sat} is exceeded. The legal situation of the reactive power control of charging stations has not yet been precisely defined. With regard to reactive power supply capability, charging stations represent a new consumer representative. VDE-AR-N 4100 [7, p. 54] of April 2019 refers only to DC and inductive charging stations. Here, the distribution system operator may specify a reactive power control capability in the range of 0.9 inductive and capacitive via an interface on charging stations with a rated power of more than $S_r = 12\,\text{kVA}$. This requirement is also to be extended to AC charging stations in the future [7, p. 54]. However, it can be assumed that the charging stations will have a similar reactive power supply as photovoltaic plants. For photovoltaic plants with a maximum apparent power $S_{Emax} < 4.6kVA$, it must be possible to set a reactive power control up to $cos(\varphi) = 0.95$ without causing a reduction of the active power. For photovoltaic plants with a maximum apparent power $S_{Emax} > 4.6kVA$, a power factor of $cos(\varphi) = 0.9$ must be possible. The reactive power is plotted in the left diagram and shows the ratio between the reactive power and the maximum apparent power S_{Emax}, whereby the reactive power saturation value can be given as $Q_{(sat,cos(\varphi)=0.95)} = 0.312$ or $Q_{(sat,cos(\varphi)=0.9)} = 0.436$. If the saturation voltage Δu_{sat} is exceeded, the active power is reduced proportionally to the voltage deviation Δu . The presented autonomous control mechanism solves voltage band violations without communication and interaction with other software agents. However, it can happen that voltage band violations do not occur directly at the actuator node. In addition, the identification of cable overloads is also not possible with the autonomous control unit. Therefor a control mechanism is necessary, which has a global view on the grid situation. For this global view several software agents have to interact together. This control concept is referred to as an interactive, coordinated control concept and is described in the following section.

B. Interactive, coordinated Control Mechanism

To detect global grid problems like cable overloads or voltage boundary violations, the topology of the autarkic grid and all incoming and outgoing measurements are required. The District agent has this information and can calculate the actual grid state of the entire distribution grid. Therefore, the District agent is predestined to be an important component of this interactive control mechanism. In the already developed GAS, a single, central PC develops control strategies for solving grid problems [8, p. 67]. Here the central PC requires detailed models of the actuators include the type of actuator (load or feeder), the possible setpoints and the local objectives of the actuator. The central PC calculates a control strategy and directly sets a setpoint for the actuator. As the number of actuators with constant model detail increases, the development of control strategies becomes more and more complex. According to [7, p. 2], in large-scale systems such as large distribution grids with many actuators, suitable control strategies can no longer be developed with omnipotent solvers. The approach arises to distribute the detailed actuator properties among the actuator agents. In an abstract sense, the competence or knowledge is divided from a single omnipotent calculation unit into several decentralized calculation units. The distribution of competence, however, involves additional effort in communication. The software agents have to interact and cooperate with each other in order to develop a suitable control strategy. The Contract Net Protocol was established in the early 1980s [9, p. 1] as part of the research area of artificial intelligence for distributed problem-solving procedures and coordination of distributed calculations. The Contract Net Protocol supports the property of resource allocation to several calculation units and focusing or bundling of tasks for optimized problem solving [9, p. 1]. In the following figure, the Contract Net Protocol is applied to the application case for solving global grid state problems and is generally divided into four consecutive phases. As shown in Figure 4, the Contract Net Protocol is divided into a problem recognition phase, an announcement phase, a bidding phase and an awarding phase. Negotiations using the Contract Net Protocol are conducted between the District agent and all actuator agents of the autarkic grid. For a better overview in Figure 4,

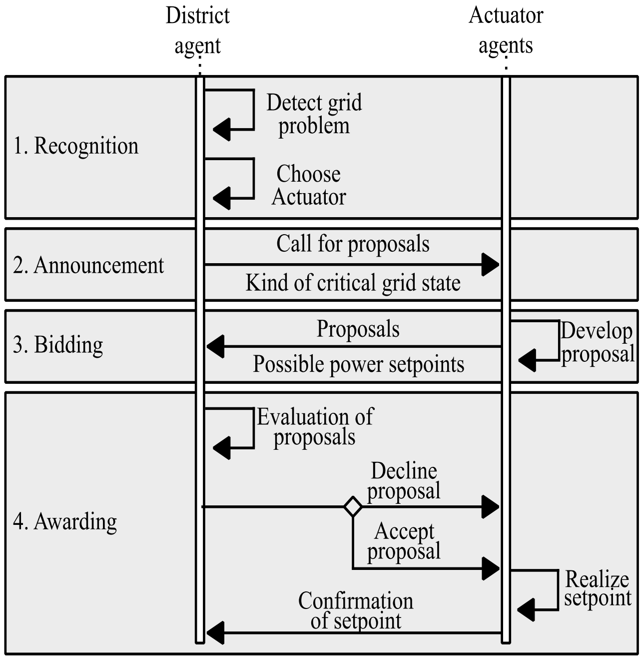

Figure 4: Phases of Contract Net Protocol to solve critical grid situations [10]

all actuator agents are bundled in the figure. The District agent acts as auctioneer within the scope of this negotiation and manages in particular the initiation and scheduling of the negotiation. The District agent calculates the actual grid state and is able to detect critical grid states. Here, the District agent continuously pursues his goal of avoiding critical grid states. In the case of an occurred grid state violation, the District agent opens the Contract Net Protocol and contacts all actuator agents. The Call for Proposals contains the grid state problem in a qualitative description type. In this control mode the actuator agents do not need any further information regarding the grid state problem. Within the framework of this interactive, coordinated control, several actuator agents can contribute to the solution of the grid state problem, so that the respective actuator agent does not know how the grid state is changed by its own control. For this reason, a qualitative description of the grid state problem is sufficient. When the actuator agents receive the call for proposals, the autonomous control mechanism is blocked. The actuator agents generate a list θ_a of possible apparent power setpoints s_{pos} with associated priorities ψ based on their local objectives and their actuator model as part of the bidding phase. An apparent power setpoint consisting only of a reactive power control receives a priority ψ=0, because a reactive power control does not represent a loss of quality with regard to the achievement of the charging objective. However, if the apparent power setpoint consists of an active power reduction, two different priorities can be assigned. If an active power control is carried out which only violates quality losses, but not the local objective of the actuator agent, a priority of $\psi = 1$ is assigned. If an active power control is performed that only increases the charging time, but does not violate the charging objective of the customer, a priority of ψ =1 is assigned. All possible apparent power setpoints are sorted according to the assigned priority ψ, whereby the first apparent power setpoint represents the preferred proposal and the last list entry the apparent power setpoint with the largest violation of the charging objective. After all actuator agents have sent a proposal to the District agent, the awarding phase is started, which represents the fourth and last phase of the Contract Net protocol. In the fourth phase, the network district agent has all the proposals of its contacted actuator agents, which are stored in a vector $\theta_t = [\theta_{a1}; \dots; \theta_{an}]^T$ with possible proposals. For organizing the proposals better, the proposals of the actuator agents are sorted according to their influence on the solution of the grid state problem and evaluated according to their influence. For illustration purposes, the sequence of the fourth phase is described using the example of a voltage band violation. The control deviation of the nodal voltage $\underline{u}_s$ of the worst node and the rated nodal voltage $\underline{u}_r$ can be determined by

$$\Delta \underline{u}_e = \underline{u}_s - \underline{u}_r. \tag{1}$$

The District agent analyses each element of the θ_{ges} vector and checks whether the selected Apparent Power setpoint s_{sp} solves the grid state problem. The results of the calculation are added to the result vector θ_{res}. The District agent executes a power flow calculation, which adjusts the nodal power of the considered actuator to the respective setpoint and keeps the remaining nodes unchanged. The newly calculated nodal voltage u_{PFC} is compared with the actual nodal voltage u_{act}. The deviation of the controlled nodal voltages $\Delta \underline{u}_c$ can be described in

$$\Delta \underline{u}_c = \underline{u}_{act} - \underline{u}_{PFC}. \tag{2}$$

In the next step, the system checks whether the necessary condition

$$\begin{cases} \Delta \underline{u}_c \geq \Delta \underline{u}_e, & \Delta \underline{u}_e > 0 \\ \Delta \underline{u}_c \leq \Delta \underline{u}_e, & \Delta \underline{u}_e < 0 \\ \quad i_c < i_{therm} & \end{cases} \tag{3}$$

is already fulfilled by the setpoint. The value i_c is the cable current and i_{therm} the maximum thermal overload current. If the necessary condition is fulfilled, the setpoint can be forwarded to the actuator agent. However, it is possible that the control of one actuator agent does not completely solve the grid state problem. In this case, the apparent power setpoint of the next actuator is added to the result vector. Then the power flow calculation is repeated and the necessary condition (3) is checked again. If the control of all previously selected cannot solve the grid state problem, the apparent power setpoint of the actuators with the higher priority is selected. The setpoints with a higher priority have a bigger influence on the solution of the grid state problem, but tend to violate the loading objectives of the actuator agent with a higher probability. In addition to the necessary condition (3), the District agent follows the sufficient condition

$$\min f(\underline{s}_{i,sp}) = \sum_{i=1}^{i=v_{pr}} (v_{pr}+1)^{\psi_i(\underline{s}_{i,sp})}, \tag{4}$$

which aims at minimizing all selected priorities ψ_i with the number of used proposals v_{pr} depending on the selected apparent power setpoint $\underline{s}_{i,sp}$. Due to the special form of the exponential equation, the sum of all proposals of one priority level is always lower than one proposal of the next higher priority level. The minimization requirement according to (4) ensures that first the control potential of the reactive power control is fully utilized before the active power control with quality losses and the active power control with violation of the load objectives are used. After the District agent has fulfilled the necessary condition (4) the apparent power setpoints $\underline{s}_{i,sp}$ of the result vector are finally forwarded to the respective actuator agents in the form of an agent message with the note "Accepted". The actuator agents, which have not been awarded for a contract, receive an agent message with the note "Discarded". The actuator agents realize the apparent power setpoints $\underline{s}_{i,sp}$ and confirm the realisation of the setpoints. Every actuator agent of a charging station is interested in increasing the apparent power in order to archieve the load objectives in the best possible way. Therefore, the actuator agents initiate a request to leave the actual apparent power setpoint in the form of an agent message after a time t_{stop}. The agent message contains the desired apparent power setpoint of the actuator agent and is transmitted to the District agent. The District Agent verifies that the desired apparent power setpoint does not cause a new grid state violation. If the desired apparent power setpoint does not result in a new violation of the grid state, the actuator agent receives a confirmation, otherwise a rejection is transmitted. The actuator agent will initiate this request again and again after the time t_{stop} has elapsed until the District agent grants approval.

In summary, an interactive coordination paradigm was used to eliminate critical grid states, in which the District agent represents the upper functional unit and the actuator agents the lower functional units, which are connected to the physically existing peripheral units in the form of the actuators. The competence is distributed decentrally among all software agents, so that the design of a control strategy is made possible by a large number of software agents. Each actuator agent determines the apparent power setpoints and correlated priorities on the basis of his own control model. The control model for a charging station agent is described in the following section.

IV. Control Model for Charging Stations

The prioritization of possible setpoints is based on a control model, which is presented in this section. According to [3, p. 68], the control of charging stations can be optimised by providing complete user information on mobility requirements. The idea of managing sensitive user information in a decentralized manner within an actuator agent and making it available to the DSOs automation system in a reduced form is enabled by the paradigm of the software agent. The reduced form is a prioritization factor ξ, which is determined by the charging station agent and is based on user information. Via a user interface, as described in [96, p. 3], the user information can be communicated to the software agent located in the local calculation unit at the charging station. The user information consists of the planned departure time t_{end}, the battery capacity of the electric car c_{bat} and the state of charge of the battery $SOC(t_0)$. If the software agent of the charging station is involved in the Contract Net Protocol, the software agent will develop a prioritization factor. Based on Figure 5, the prioritization factors are determined as a function of the possible apparent power setpoints of the charging station.

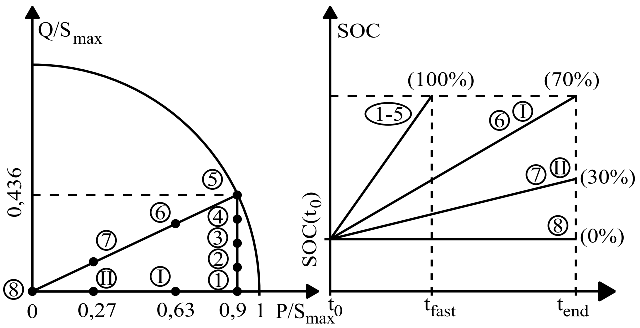

Figure 5:Left: Operating points of a charging station, Right: SOC of an electric car at different operating points of the charging station

The left partial figure shows the possible apparent power setpoints of the charging station in a P/Q diagram. The right partial figure shows the charging behaviour of the electric car battery, which results from the selected operating point of the left partial figure. The operating points of the right partial figure result from the requirements for active power control of charging stations according to [7, p. 55] with a rated power $S_n > 12kVA$, which suggests the possibility of stepwise control in 10% steps. For reasons of simplicity, fewer control stages than in reality have been drawn in figure 5. The VDE standard 4100 provides for reactive power supply in the future [7, p. 54], which has not yet been described in more detail. Therefor the reactive power supply capability for photovoltaic plants is used as a template. The default state is defined as operating point 1, which defines the maximum active power without reactive power supply. The charging station will provide a maximum of $p_{max} = 0.9 \cdot S_n$ to enable a reactive power supply up to a maximum of $cos(\varphi) = 0.9$, without the need of a reduction of the active power (see operating points 2 to 5). If the active power is reduced, the reactive power can be adjusted in the same power factor ratio in order to achieve effects on voltage changes. In the case of a voltage band problem, operating points 6, 7 and 8 are entered in the vector θ_{ges}. In the case of a cable overload, the operating points I, II and 8 are entered in the vector θ_{ges}. Afterwards the Colomb-Counting Law

$$SOC(t) = SOC(t_0) + \frac{1}{c_{Bat}} \int_{t_0}^{t_{end}} i_l(t)\, dt, \qquad (5)$$

which determines the state of charge of the electric car battery as a function of the charging current i_l and the capacity of the battery c_{Bat} .The charging current i_l is measured and provided by a corresponding sensor agent. Since the measurement information is processed and transmitted in discrete time steps, the following changes occur

$$SOC[t] = SOC[t_0] + \frac{\mu_L}{c_{bat}} \sum_{i=i_0}^{i_{end}} p_l \cdot [t_{i+1} - t_i], \qquad (6)$$

which is a discrete-time description of eq. (5). In addition, the charge current is described by the charge power p_l and the node voltage u_n. The charge efficiency μ_L is also introduced. By changing the eq. (6), the necessary charging time

$$t_L = c_{Bat} \cdot u_n \frac{SOC_{des} - SOC(t_0)}{\mu_L \cdot p_L} \qquad (7)$$

is calculated with desired state of charge SOC_{des} and the assumption that the charging power p_L and the nodal voltage u_n remain constant over the charging time. The charging station agent checks whether the set operating point violates the following condition

$$t_{end} \geq t_0 + t_L. \qquad (8)$$

In the case of operating point 1, no control is performed and the prioritization factor ξ=0 is assigned. At operating point 2-5, a prioritization factor ξ=1 is assigned, because a control is executed, but this operating point has no negative influence on the loading time. Operating points I and 6 extend the loading time, but condition (8) is still fulfilled, so that these operating points also receive the prioritisation factor ξ=1. For working points II, 7 and 8, the loading time exceeds the desired time t_{end}, which is sanctioned with a prioritisation factor of ξ=2. The software agent of the charging station will store all operating points with their corresponding prioritisation factors in the vector θ_{ges}. This vector is finally sent as a proposal to the requesting District agent. In summary, the software agent of the charging station calculates a vector θ_{ges} with possible operating points and corresponding prioritization factors based on the described model and the user information. The vector θ_{ges} represents a reduced and simplified information content for the District agent. However, this reduced information content is sufficient for the District agent, because the District agent only needs the information about the possible operating points and their priority. Sensitive information, such as the desired departure time, remains locally on the charging station agent and is not transmitted to the DSO.

V. Critical Analysis of the Control Mechanism

For the critical analysis of the presented control mechanisms, a mind experiment is carried out, which is divided into two scenarios in the following figure.

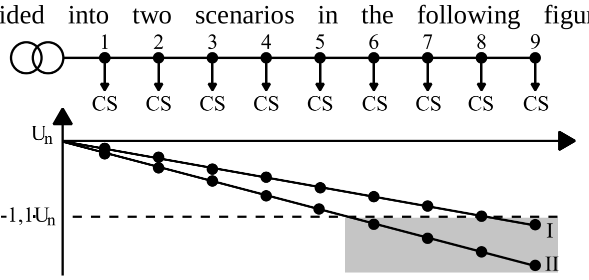

Figure 6: Scenarios for the analysis of coupling effects of several decentralized controllers

Figure 6 shows the voltage curves of a grid for two different load scenarios caused by controllable charging stations (CS). In scenario I, the lower voltage band $(-1.1 \cdot u_n)$ at node 9 is violated. The sensor agent of node 9 will forward the measurement information to the actuator agent and calculate the control deviation Δu_e. Based on the characteristic curve from Fig. 3, the autonomous controller will send a setpoint to the real actuator. After the setpoint has been realized, the grid state will be improved or be completely eliminated. The sensor agent will again transmit its measurement information to the actuator agent, so that a new control deviation can be calculated. The actuator agent will determine that the currently realised setpoint is too high in relation to the actual grid state and will adjust the setpoint in the next control step. The described procedure will be repeated and the entire system will start to oscillate. In order to prevent this oscillation characteristic caused by the control, it is necessary to adapt the control characteristic curve from Fig. 3. The following figure shows an optimized characteristic curve with improved control characteristics.

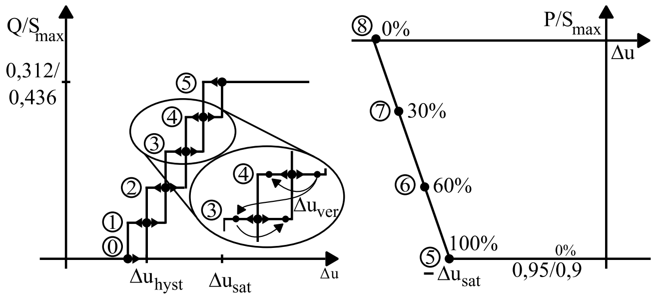

Figure 7: Improvement of the control characteristics by implementing hysteresis for reactive power control and predictive calculations for active power control

In Figure 7, the reactive power control is combined with a hysteresis characteristic. The active and reactive curves are adjusted with discrete setpoint values. In this example, operating point 4 is set. Operating point 4 will lead to a reduction of the control deviation Δu, whereby the previous controller would change the realised setpoint again. By introducing a hysteresis characteristic, operating point 4 will lead to a reduction of the nodal voltage Δu_{ver}, but generally does not lead to a new operating point (see Fig. 7). If the hysteresis range is left and a new operating point is set, the controller is designed to prevent a jump back effect to the previous operating point. However, it can also happen that the load situation leads to a change in the control, whereby the hysteresis range of the selected operating point can be left and a new operating point can be set. This ensures that the autonomous controller continuously adapts to the actual situation in the distribution grid. If the control deviation is $\Delta u > \Delta u_{sat}$, the autonomous controller would begin to reduce the active power as a function of the control deviation. As already described, the controller has value-discrete control stages so that one of the operating points 6 to 8 is selected. The active power reduction will lead to an improvement of the grid state. It is possible that the control deviation becomes $\Delta u < \Delta u_{sat}$, whereby the autonomous controller deactivates the active power control. This effect will lead to an oscillation of the entire system, because of the time delay between the new control deviation and the realised setpoint. The introduction of a hysteresis characteristic similar to that of reactive power control could solve the oscillation problem, but is not advisable. The hysteresis characteristic as part of the active power control would release the active power control setpoint with a time delay. Even if the criticality of the grid state no longer requires an active power control. For this reason the hysteresis characteristic is not suitable for the active power control. Even before a new operating point is realised, the autonomous controller must know, how the new setpoints affects its nodal voltage. In order to be able to determine this influence quantitatively, a linearization factor $\underline{m}$ is initially transferred to the autonomous controller. The linearization factor $\underline{m}$ describes the influence of the power change on the voltage change in a linearized form. The relationship

$$\Delta u_{\Delta p}(\Delta p) = \left|\frac{\underline{m} \cdot \Delta p}{\underline{u}_n}\right|, \tag{9}$$

can be developed, which describes the voltage change $\Delta u_{\Delta p}$ as a function of the active power change Δp. The autonomous controller will use eq. (9) to calculate the voltage change $\Delta u_{\Delta p}(\Delta p)$ for control stages 30, 60 and 100% of active power and decide whether the withdrawal of the active power reduction leads to a renewed grid state violation. This calculation is started with each new measurement information from the sensor agent. Thus, the actuator agent can continue to pursue its local objective and guarantee the maximum possible active power utilisation. If several actuators are installed at one node, the actuators are handled together and controlled by a single actuator agent. In scenario I, the oscillation behaviour of a single, autonomous controller is investigated. However, a grid state violation can occur at several nodes, which defines scenario II. Each node is equipped with an autonomous controller, which will perform a control to remedy the detected voltage violation. A feedback effect of all autonomous controls can occur, which represents a positive, additive feedback of the output signal to the system input. This feedback effect results from the time delay of the controlled system, which is provided to the autonomous controller with a time delay in the setpoint-actual value comparison. This time delay can cause an oscillatory behaviour. In order to prevent this negative coupling effect, the autonomous controllers must be activated according to a time staggering. The time staggering is also used for the selective tripping of line contactors within the scope of protection technology of distribution grid and can be used as an orientation aid. With an independent maximum current timer relay (UMZ protection), for example, the protective device is tripped if the current threshold value exceeds an adjustable tripping time [11, p. 344]. In order to guarantee the selectivity of the line sections for radiation grids, the switch-off times of the UMZ protective devices increase in the direction of the transformer. In other words, the autonomous controller that has the largest line impedance between itself and the transformer should have the shortest tripping time and accordingly activate the control first. The question arises whether this principle can be applied to the time staggering of the autonomous controllers. Furthermore, the question arises whether the autonomous controller with the "smallest" or "largest" distance to the transformer should be activated first. In scenario II, the decision must be made whether the autonomous controller should be activated at node 6 or node 9. For node 6 in Fig. 6, the nodal voltage can be calculated by

$$\underline{u}_6 = \underline{z}_{06} \cdot (\underline{i}_6 + \underline{i}_7 + \underline{i}_8 + \underline{i}_9), \tag{10}$$

which is composed of the line impedance z_{06} between the transformer and the network node 6 and the node currents of the actuator 6 to 9. The nodal voltage of node 9 is defined by

$$\begin{aligned}\underline{u}_9 = \underbrace{\underline{z}_{09} \cdot \underline{i}_9}_{\underline{u}_{98}} + \underbrace{\underline{z}_{08} \cdot \left(\underline{i}_9 + \underline{i}_8\right)}_{\underline{u}_{87}} + \underbrace{\underline{z}_{07} \cdot \left(\underline{i}_9 + \underline{i}_8 + \underline{i}_7\right)}_{\underline{u}_{76}} \\ + \underbrace{\underline{z}_{06} \cdot \left(\underline{i}_9 + \underline{i}_8 + \underline{i}_7 + \underline{i}_6\right)}_{\underline{u}_6}.\end{aligned} \quad (11)$$

In summary, actuator 9 receives the smallest delay time $t_{del,9}$, because this actuator is furthest away from the transformer. Before actuator 8 is activated, actuator 9 must have already realised the setpoint and actuator 8 must still have detected the grid state violation. The delay time of actuator 8 is accordingly calculated by

$$t_8 = \mathrm{t}_{\mathrm{del},9} + t_{det} + t_{real}, \quad (12)$$

with the time delay $\mathrm{t}_{\mathrm{del},9}$ of actuator 9, with the detection time t_{det} to detect the grid state problem and with the realisation time $t_{real,9}$ to realise the desired setpoint. The control applied to actuator 9 results in the control deviation for actuator 8 becoming smaller and the autonomous controller being able to indicate a new setpoint without an oscillation of the entire system. In general, the trigger time $t_{a,i}$ can be set via

$$\mathrm{t}_{\mathrm{a,i}} = (n - i) \cdot (t_{det} + t_{real}) + (n + 1 - i) \cdot t_{del} \quad (13)$$

where n is the total number of all actuators and i is the respective actuator. The cancellation of the control interventions of the autonomous controllers is carried out according to

$$t_{d,i} = (\mathrm{i} - 1) \cdot (\mathrm{t}_{det} + \mathrm{t}_{\mathrm{r}}) + \mathrm{i} \cdot \mathrm{t}_{\mathrm{del}}. \quad (14)$$

In summary, the stability control mechanisms were not examined with regard to their stability and suitable mechanisms were found which guarantee the stability of the entire system.

VI. Conclusion

In this paper two different agent-based mechanism for the control of charging stations are presented. One mechanism provides an autonomous control of charging stations, which can be implemented without communication effort and without a holistic view on the entire distribution grid. This control mechanism is able to detect voltage boundary violations and is activated by a time staggering. In the second mechanism, the interaction of multiple software agents helps to develop control strategies to solve global grid state problems. Each software agent has different local objectives and a local control models. By partition the calculation into several decentralized calculation units and software agents, the entire problem is divided into subproblems. The subproblems can be modelled by the presented control model of a charging station agent. Summarizing, the paradigm of a multi-agent systems is able to develop different control mechanism for charging stations.

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