Swarm-based automation of electrical power distribution and transmission system support

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Abstract: The increasing amount of distributed energy resources installed in distribution systems imposes new challenges on the operation and control of both distribution and transmission systems. At the same time, most distributed energy resources have the potential to support grid operation, e.g. as reactive power suppliers. To exploit these capabilities, a flexible and scalable control approach capable of dealing with large numbers of heterogeneous components is required. Many approaches are either distribution or transmission oriented and neglect the interests or constraints of the other side. Furthermore, the drawbacks of classical centralised control are often ignored. This study presents SwarmGrid-X, an agent-based control concept that considers the structure, demands and capabilities of components in the distribution system and the power requirements of the transmission system at the point of common coupling. Agents control components autonomously and determine control decisions in a decentralised way. They cooperate in swarms to achieve a common system goal while information and power flow are kept as local as possible. The cooperative nature of SwarmGrid-X transforms the distribution system into a cyber-physical power system. This study explains how SwarmGrid-X enables cyber-physical interactions of components to automate electrical power distribution and support the transmission system.

1 Introduction

Power grids are undergoing tremendous changes due to the installation of large amounts of distributed energy resources (DERs) in distribution systems. In traditional power grids, large generation units are connected to the transmission grid and power is transported to distribution grids which supply industrial and commercial as well as household loads. However, now more and more generation is connected directly at the distribution level. Such units are renewable energy resources (mainly photovoltaic (PV) systems and wind energy converters (WECs)) but also combined heat and power (CHP) systems coupling electrical and thermal power supply. Additionally, new types of loads, the electric vehicles (EVs), further stress the grid. For grid operators, this large number of DERs poses new challenges to maintain a safe grid operation. Among other technical constraints, distribution system operators (DSOs) have to ensure that the voltage at each node remains within an acceptable range. For this purpose, current grid codes enforce DERs to allow curtailment according to predefined characteristics [1, 2]. Transmission system operators (TSOs) are obliged to maintain the system frequency and to adjust power production and consumption at all times. This becomes more complex since power reserves in the transmission system – which are traditionally used to achieve the adjustment – are decreasing. However, an activation of power reserves in the distribution grid to support a TSO should not interfere with the tasks of a DSO and vice versa.

As a consequence, the need for a control system capable of dealing with the described challenges arises. Classical systems comprising supervisory control and data acquisition and control centres are centralised and have a single point of failure and limited scalability. The latter is especially critical considering the large number of heterogeneous DERs in the distribution systems. As a result, many decentralised control schemes have been proposed to deal with voltage control, fault isolation and restoration as well as power management in the literature (see Section 2.1).

Systems, as described here, are often referred to as cyber-physical power system (CPPS). In contrast to a classical power system, a CPPS is heavily based on information and communication technology for control purposes [3]. Hence, CPPSs are characterised by strong interdependencies between power grid and information and communication technology. This study outlines how an agent-based approach relying heavily on communication among agents can help the integration of DERs in CPPSs.

In [4], the authors utilise a multi-agent system (MAS) approach for a swarm-based control called SwarmGrid. Each DER in the grid is represented by one agent. Each agent is able to exchange information with other agents, obtain local sensor values and control its DER. The main target of SwarmGrid is the local adjustment of active and reactive power production and consumption in a low voltage (LV) grid. To achieve this, various protocols based on standards of the Foundation for Intelligent Physical Agents (FIPA) are utilised for negotiation among agents. The SwarmGrid concept is applied to a single LV grid and demonstrated in a simulation. The key contributions of this study are the following extensions of SwarmGrid control:

- Decentralised voltage control for multiple voltage levels.
- Support of the transmission system by means of adjustable active and reactive power provision without harming the operation of the distribution grid.

Regarding the control of multiple voltage levels, medium voltage (MV) grids differ from LV grids in the installed power per DER. Moreover, most nodes contain underlying LV grids which behave like a producer or consumer in the MV grid. Furthermore, a simple adoption of SwarmGrid control as in [4] would lead to a large number of potential communication partners for each DER agent. To overcome these difficulties we propose SwarmGrid–X (SwarmGrid–eXtended): a hierarchical swarm-based control concept reflecting the inherent hierarchy of a power grid. Communication among DER agents takes place only within one voltage level and subgrid. In case an adjustment of power is impossible in a subgrid, the corresponding substation, which is also controlled by an agent, is contacted. It has the task to forward the needs of the LV grid to the MV level. Doing that, it behaves like a...
consumer or producer in the MV grid. If the LV grid has a certain degree of flexibility, the substation offers this flexibility in the MV grid and contacts the flexible DERs in case this flexibility has to be activated. On the other side, the substation agent searches for producers in the MV grid if the LV grid cannot cover its demand by itself. The same methodology for agent interactions as in the LV grid is applied in the MV grid resulting in a holonic MAS. It is also applied to the interface between MV and high voltage (HV) grid. Additionally, a specialised agent introduces the requirements of the superordinate grid (normally the transmission system) to the MAS by interacting with the primary substation. This agent behaves like a consumer or producer of active and reactive power according to what is needed to support the superordinate grid. Thereby, the distribution system helps the superordinate grid operator (i.e. the TSO) with the provision of active or reactive power for voltage support or reserve power activation.

This study deals with the technical feasibility of a swarm-based distribution grid control with respect to the two scientific contributions mentioned above. Both aspects are analysed by means of simulations. For a real-world application, it would have to be integrated into a broader system considering also market roles, reimbursement of participating DERs and security aspects of communication technologies. An example of a market-based approach which considers different roles such as aggregators, and DERs can be found in [5]. While power schedules based on market activities are usually determined hours to day-ahead, DERs adjust their set points of active and reactive power in an ad-hoc way according to the current situation in SwarmGrid-X. Consequently, they are also able to deal with unforeseen events such as an outage of another DER or forecast errors. Regarding the provision of active or reactive power to the transmission system, long-term subordinates describing the requirements of the transmission system as well as short-term requests can be handled.

The paper is organised as follows: Section 2 covers the related research regarding decentralised distribution grid control, the coordination of different voltage levels and transmission system support by distribution grids. Also, the most important currently valid German regulations for the operation of DERs are discussed and an overview of the exchange between DSO and TSO is provided. Section 3 describes the proposed concept by first recapturing the SwarmGrid control approach. Then the extension to multiple voltage levels and transmission system support for SwarmGrid-X are explained. For the evaluation of SwarmGrid-X, Section 4 introduces the applied methodology and Section 5 analyses the obtained results. Section 6 concludes this work and provides an outlook on the next steps to be taken.

2 Related research

2.1 Decentralised distribution grid control

The diffusion of information and communication technology in distribution grids transforms them into cyber-physical power systems enabling cooperative and coordinated control along with peer-to-peer data exchange between actors. Decentralised control concepts become feasible, as intelligence does not have to be centralised any more but can be distributed in the system and connected by information and communication technology. Major motivators for decentralised control are the increased scalability of the control solution and its enhanced robustness against a single point of failure compared to centralised approaches.

The literature provides many decentralised control concepts for distribution grids. However, these concepts have different notions of decentralisation. Decentralised concepts for DER dispatch [6], economic or energetic optimisation [7] or the web-of-cells approach [8] have been proposed. These three exemplarily chosen approaches have in common that decentralisation refers to the level of information acquisition but not to the determination of all control decisions. For this reason, their control decisions are vulnerable to single point of failures while at the same time their scalability is limited by the complexity of the global optimisation problem. To overcome these issues, the concept presented in this work uses a decentralised control where data is kept as local as possible and the control decision making is fully decentralised.

MASs are a promising concept to implement decentralised distribution grid control [9]. However, they also introduce new challenges, such as the mapping of agents to components and decision makers of the distribution system. Also, the mutual work of agents for one shared global goal has to be shaped. Many agent-based control concepts in the literature use a MAS to determine the value of a global system state variable without having to measure and broadcast the value of the variables. Especially, if applying an agent-based consensus algorithm for this purpose is popular in the literature [12–17]. The value of the global system state variable (e.g. voltage or frequency) is the basis of the local control of agents and drives the overall system behaviour to a certain direction. Consequently, it can also drive the system behaviour to the wrong (or non-optimal) direction if errors or manipulations occur in the consensus algorithm. For that reason, all decision making in SwarmGrid-X is based solely on locally available information and agreements that are found with explicit other agents, but not all others.

For SwarmGrid-X, we use the MAS concept to represent a CPPS. Agents represent components of the distribution system such as loads, generators, storages, and transformers. They make their control decisions autonomously, based on own behaviour rules, reasoning, and coordination with other agents. A global system state variable is not considered for local decision making in SwarmGrid-X. This approach keeps the sovereignty of control decisions at the owners or operators of the DERs and considers their interests and constraints. The global system state is unknown to any DER participating in SwarmGrid-X. In contrast to other agent-based control approaches [18, 19], SwarmGrid-X enables a flexible formation of cooperating agents as swarms which adapt to the situation of the electrical grid.

2.2 Coordinated control of multiple voltage levels

Additional challenges for decentralised distribution grid control arise when the grid hosts multiple voltage levels. The number of DERs – and thereby the complexity of the control – grows with the voltage levels. The hierarchical structure of the grid demands a coordination of actions among voltage levels. For example, the position of the on load tap changer (OLTC) of a primary substation influences the voltage of the entire distribution grid and should, therefore, be coordinated with the tap settings of secondary substations. Moreover, the tap position might influence the reactive power behaviour of underlying DERs possibly affecting the voltage quality in the primary grid [20].

Different concepts have been proposed in the literature to cope with these challenges. A concept for voltage maintenance and congestion prevention based on substation automation units (SAUs) [21] has been applied to MV and LV networks [22]. The top layer of hierarchy is the control centre [23]. An automation unit located at primary and secondary substations is responsible for monitoring and control of the underlying grid and DERs located in that grid. However, the control hierarchy might impose timing problems or interlocking, since each layer requires the calculation output of the lower layers for a proper operation. For SwarmGrid-X, we seize the idea of control distribution to substations and shift the control decisions deeper into the distribution system, i.e. to the DERs themselves.

Another example of a hierarchical control structure can be found in [24]. SwarmGrid-X, we seize the idea of control distribution to substations and shift the control decisions deeper into the distribution system, i.e. to the DERs themselves.

In another example of a hierarchical control structure can be found in [24]. A network supervisor located at the primary substation clusters the LV network and determines a voltage set point for each cluster. DERs in a cluster adjust their reactive power behaviour according to a Q(V) curve. Similar to the SAU concept, the single LV grids are still controlled centrally. Additionally, the clustering of LV networks is also computed centrally by the network supervisor. This leads to increased computational burden compared to a fully decentralised scheme such as SwarmGrid-X and introduces a single point of failures, at least for subparts of the system. Similar considerations apply for concepts in which community cells [6] or microgrids [25] are used as smallest control units and a hierarchical control scheme is formed by clustering of these units.
One example of a fully distributed control concept is so-called holonic systems. A holon is defined as an autonomous and cooperative unit which itself can consist of multiple smaller child holons. Thereby, holons form a recursive structure which is often referred to as holarchy [26]. In [26], a general architecture of distribution grids utilising holons is described. Prosumers with both power producing and consuming DERs form the lowest layer of the holarchy. They cooperate with other prosumers and form larger parent holons which behave like prosumers in the next layer. This architecture can be recursively repeated to cover the whole distribution system. Global goals are achieved by cooperation among holons within the same layer and by utilising the capabilities of holons in the underlying layer. At the same time, holons can request help from their parent holon for reaching their individual local goal. The concept of holons has been exploited for distribution system control in different ways [27, 28].

A holonic control architecture offers several benefits: it introduces a hierarchy as well as a completely distributed control within one layer so that there is no single point of failure. Therefore, SwarmGrid-X makes use of some features of holonic control. Single DERs are considered as the lowest layer of the hierarchy and act autonomously. Each voltage level forms a new parent holon which is represented by the respective substation in the next higher layer. This structure is repeated for each voltage level. Communication among agents takes place only within one layer or with the substation. For the cooperation among agents in the same layer, we add the concept of swarms as explained in detail in Section 3.2.3

### 2.3 Transmission system support by distribution grids

Using distribution systems to support the operation of transmission systems is not a novel idea. In [29], significant potentials of doubly fed induction machines and OLTCs in distribution systems for reactive power supply in the transmission system have been identified. This motivates a deeper look into interaction strategies between distribution and transmission systems. Cuffe and Keane [20] present a strategy that makes reactive power flows from DERs responsive to transmission system voltages. Their results indicate that the control of a distribution system for transmission system support does not have to be centralised or happen outside of the distribution system. It is feasible from inside the distribution system, without a centralised computation of control signals being required for all DERs in the distribution system. This is also shown in [30] where a MAS approach is used to provide reactive power support. The idea is seized and extended in SwarmGrid-X by defining interaction behaviours for distribution system components which enable the overall system to follow a power set point defined by the transmission system (operator).

A top-down control approach based on the incident command system is proposed in [31]. Top-down approaches in general face scalability under increasing system size and complexity. Furthermore, especially in the incident command system, the failure of a central authority implies uncoordinated behaviour of all subordinate units, which we regard as another disadvantage.

Some control approaches aim at minimising the reactive power exchange with the transmission system by using pre-defined configuration parameters for generators, substations or controllers [32, 33]. We believe that a real-time control is required in a real system to react to changes in a flexible way. Furthermore, from the perspective of a TSO, defining a specific set point for reactive power exchange with a distribution system seems more attractive than simple minimisation as this would enable to a more flexible operation and more accurate voltage support. Hence, SwarmGrid-X provides such a functionality, allowing a TSO to request active or reactive power from a distribution system at the point of common coupling.

It is inevitable that a TSO’s request complies with the technical limits of a distribution system. The authors of [34] analyse DSOs as service providers for TSOs with respect to reactive power. They suggest a separate optimisation of distribution and transmission systems where the boundaries of reactive power of the distribution system are an input for the optimisation of the transmission system. In our opinion, a DSO needs to exchange its active and reactive power flexibilities with a TSO before any request can be issued by a TSO. For this purpose, the capability of the distribution grid to provide active or reactive power to the transmission system is aggregated at the point of common coupling in real time.

### 2.4 Regulations and roles

The growing number of DERs in distribution systems has enforced new grid codes regarding their active and reactive power characteristics. In Germany, mainly two regulatory works define the requirements for installation and operation of DERs in LV and MV grids [35, 36]. An overview of European grid codes for PV and WEC integration can be found in [1, 2, 37]. Most grid codes require the ability to curtail active power supply from DERs in order to mitigate line congestions and voltage band violations caused by DERs. Regarding reactive power, DERs must be able to adjust their power factor in a defined range, either based on the utilisation of the DER (cos(\(\phi\))P) or based on the voltage measured at the point of common coupling (Q(V), \(\Delta Q(V)\)). These methods do not exploit the full potential of DERs and can even stress the transmission system due to additional losses caused by reactive power [38]. We believe that an individual reactive power set point for each DER considering local as well as global constraints is more beneficial for voltage control and allows having a defined reactive power exchange with the transmission system. As a result of voltage quality improvements, the number of active power curtailments can potentially be reduced.

Stronger cooperation between TSO and DSOs as motivated in the previous section also requires the exchange of operational data. Approaches to estimating the active and reactive power flexibilities of a distribution grid can be found in [39, 40]. Also, new regulations on European [41], as well as German [42] level, have addressed these challenges. With SwarmGrid-X, we present a control approach that qualifies the TSO to activate a required amount of active or reactive power in the distribution grid. We do not consider restrictions by regulations or legislation but assume that DERs are in general able to participate in such a concept. For a real world implementation, regulation extensions might be necessary and reimbursement strategies, as well as market integration, have to be defined. However, this work focuses on the technical feasibility of SwarmGrid-X.

### 3 SwarmGrid-X control concept

The presented swarm concept aims at providing a fully decentralised control of DERs located in electrical distribution grids. It is an extension of the concept called SwarmGrid control described in [4] and therefore referred to as SwarmGrid-X. The architecture of SwarmGrid-X is shown in Fig. 1.

### 3.1 General concept

The following DERs are considered: loads, PV systems, WECs, CHPs, EVs, heat pumps (HPs) and batteries. Moreover, also transformers with an OLTC participate in SwarmGrid-X. Each DER is represented by an intelligent agent, which makes the decision about the control values of its DER, i.e. set point for the active and reactive power of a prosumer or tap position of a transformer OLTC. Agents interact with their environment, meaning they perform voltage or current measurements and apply control values to their component autonomously. They react to a communication received by other agents and pro-actively communicate with other agents to retrieve information and to influence the actions of other agents. All agents representing a DER installed in a distribution grid form a so-called MAS that means one entire distribution grid is represented by one MAS. Each agent has individual goals, such as coverage of a certain power demand or local voltage control. To achieve its goals each agent continuously performs a defined behaviour. Additionally, the MAS has the goal to guarantee a safe operation of the overall distribution grid, i.e. maintain voltage and...
have a defined exchange of active and reactive power with the transmission system.

Fig. 1 shows the overall structure of a distribution grid and the interactions among agents to achieve different goals. Interactions among agents within the same voltage level aim at a local adjustment of power. Hence, consumers try to find producers that can provide enough power to cover their demand as good as possible. At the same time, producers advertise the amount of power they can provide. Each agent can communicate with a set of other agents which is called a swarm. The swarm of an agent can grow or shrink in size, depending on the situation and goals that need to be addressed. For example, an increase in power demand may result in a need of more producers and therefore in a growing swarm.

In this section, we first present the behaviour and interactions of agents within a single voltage level. Subsequently, we derive the extension to multiple voltage levels based on the methodology of holonic concepts. Afterwards, it is explained how the requirements of the transmission system are introduced into the operation of the MAS. In the equations and explanations below, the following conventions are used for power values:

- \( P < 0 \): active power production.
- \( P > 0 \): active power consumption.
- \( \dot{Q} < 0 \): capacitive behaviour (reactive power production).
- \( \dot{Q} > 0 \): inductive behaviour (reactive power consumption).

### 3.2 Local power balancing

The previous version of the concept for a single LV grid has already been described and evaluated in [4]. In this section, we provide a detailed explanation of the behaviour of single agents considering [4] and further extensions. As seen in Fig. 1, local power balancing takes place at each voltage level by interactions among single prosumers.

#### 3.2.1 Prosumer active power operation range:

Prosumers are DERs that consume or produce power. Moreover, some prosumers have the capability of adjusting their reactive power behaviour by means of an inverter or a synchronous generator. To coordinate efficiently with other agents, prosumer agents continuously determine the range of active and reactive power in which they can operate. This leads to a minimum \( (P_{\text{min}}, Q_{\text{min}}) \) and a maximum value \( (P_{\text{max}}, Q_{\text{max}}) \) of active and reactive power. Additionally, the agents calculate an optimal value \( (P_{\text{opt}}, Q_{\text{opt}}) \) for active and reactive power which represents the control value the agents would like to apply in order to meet their individual goals. These values are updated at each time step with step size \( t_{\text{step}} \). The calculation of the operation range is explained for every DER in detail in the following and has the goal to operate grid supportive. As this work analyses the technical feasibility of SwarmGrid-X, the prosumers’ willingness to offer flexibility is not considered. However, the calculation of the operation range can be extended to comprise restrictions regarding the willingness to participate in the concept.

**Load:** A load is a DER with a fixed power consumption. Its demand \( (P_{\text{dem}}, Q_{\text{dem}}) \) is predetermined and cannot be altered. Hence, the operation range of a load is

\[
P_{\text{min}} = P_{\text{max}} = P_{\text{opt}} = P_{\text{dem}}. \tag{1}
\]

\[
Q_{\text{min}} = Q_{\text{max}} = Q_{\text{opt}} = Q_{\text{dem}}. \tag{2}
\]

**EV:** An EV does not have a fixed power demand. Instead, it requires a certain amount of energy to charge the battery until it disconnects from the grid. The agent of the EV is assumed to roughly know the remaining amount of time \( t_{\text{connect}} \) in which the EV is still connected to the grid. Moreover, the EV has a maximum charging power \( P_{\text{ch,max}} \) and a battery capacity \( C_{\text{el}} \). Based on the state of charge (SOC) and hence, the remaining amount of energy needed to fully charge the battery, the agent can determine the amount of power \( P_{\text{max}} \) required until disconnection:

\[
P_{\text{max}} = \frac{(1 - \text{SOC}) \cdot C_{\text{el}}}{t_{\text{connect}}}. \tag{3}
\]

As for the calculation of the maximum power, the agent must not overcharge the EV. Hence

\[
P_{\text{max}} = \min \left\{ P_{\text{ch,max}}, \frac{(1 - \text{SOC}) \cdot C_{\text{el}}}{t_{\text{step}}} \right\}. \tag{4}
\]

The optimal power is calculated so that the EV reaches a SOC of 80% as fast as possible

\[
P_{\text{opt}} = \min \left\{ P_{\text{ch,max}}, \frac{(0.8 - \text{SOC}) \cdot C_{\text{el}}}{t_{\text{step}}} \right\}. \tag{5}
\]

**PV system and WEC:** PV systems and WECs are renewable energy sources which have a power generation \( P_{\text{gen}} \) dependent on the environmental situation. As the agents controlling these components do not want to waste the produced renewable power, the operation range is

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**Fig. 1** Holonic architecture of SwarmGrid-X
\[ P_{\text{max}} = P_{\text{max}} = P_{\text{opt}} = P_{\text{gen}}. \] (6)

Battery: Similar to an EV, a battery has a maximum charging power \( P_{\text{ch, max}} \) which is considered to be the maximum discharging power as well. With the SOC and the capacity \( C_{\text{el}} \) the currently stored energy is
\[ E = \text{SOC} \cdot C_{\text{el}}. \] (7)

Hence, the maximum power is
\[ P_{\text{max}} = \min \left\{ P_{\text{ch, max}}, \frac{C_{\text{el}} - E}{t_{\text{step}}} \right\} \] (8)

and the minimum power is
\[ P_{\text{min}} = \max \left\{ -P_{\text{ch, max}}, -\frac{E}{t_{\text{step}}} \right\}. \] (9)

The goal of a battery agent is keeping the SOC in a range that enables the most flexibility offerings for other agents. That is why the agent wants to maintain a SOC of \( \sim 50\% \) as this allows the battery to both consume and supply power in equal shares. By adding a hysteresis to the battery operation, a frequent change of power from the thermal storage with thermal capacity \( C_{\text{th}} \) and the minimum power is
\[ P_{\text{min}} = \begin{cases} P_{\text{ch, max}}, & \text{SOC} < 0.3, \\ P_{\text{ctrl}}, & 0.3 \leq \text{SOC} \leq 0.7, \\ -P_{\text{ch, max}}, & \text{SOC} > 0.7 \end{cases} \] (10)

considering that
\[ P_{\text{min}} \leq P_{\text{opt}} \leq P_{\text{max}}. \] (11)

CHP: CHPs have to cover a certain thermal power demand \( P_{\text{th, dem}} \). They can do so by producing thermal power \( P_{\text{th}} \) or by providing power from the thermal storage with thermal capacity \( C_{\text{th}} \) and stored energy \( E \). The conversion factor \( f_{\text{el}} \) is used to determine the amount of thermal power produced for a given electrical power output
\[ P_{\text{el}} = P_{\text{th}} \cdot f_{\text{el}}. \] (12)

The maximum power is determined to
\[ P_{\text{max}} = \max \left\{ \min \left\{ 0, -P_{\text{th, dem}} \cdot f_{\text{el}} \right\}, -P_{\text{nom}} \right\} \] (13)

with the nominal power \( P_{\text{nom}} \). For the minimum power, the agent has to consider that the thermal storage cannot be overcharged
\[ P_{\text{min}} = \max \left\{ -P_{\text{nom}}, -P_{\text{th, dem}} + \frac{C_{\text{th}} - E}{t_{\text{step}}} \cdot f_{\text{el}} \right\}. \] (14)

Similar to the battery, the CHP agent wants the SOC of the thermal storage to remain in the range of 30–70%. The optimal power is determined to
\[ P_{\text{opt}} = \begin{cases} P_{\text{ch, max}}, & \text{SOC} < 0.3, \\ P_{\text{ctrl}}, & 0.3 \leq \text{SOC} \leq 0.7, \\ -P_{\text{ch, max}}, & \text{SOC} > 0.7 \end{cases} \] (15)

considering the relation described in (11).

HP: For the HP, the same considerations as for the CHP apply. However, instead of producing electrical power, the HP is a consumer
\[ P_{\text{hp}} = P_{\text{hp}} + P_{\text{opt}} = P_{\text{gen}}. \] (6)

Fig. 2 Reactive power operation range (for \( Q_{\text{ctrl}} = 0 \))

\[ P_{\text{max}} = \min \left\{ \max \left\{ 0, \frac{P_{\text{th, dem}} - E}{t_{\text{step}}} \right\}, f_{\text{el}} \right\} \] (16)

\[ P_{\text{min}} = \min \left\{ P_{\text{nom}} - P_{\text{th, dem}} + \frac{C_{\text{th}} - E}{t_{\text{step}}} \cdot f_{\text{el}} \right\}. \] (17)

\[ P_{\text{opt}} = \begin{cases} P_{\text{nom}}, & \text{SOC} < 0.3, \\ P_{\text{ctrl}}, & 0.3 \leq \text{SOC} \leq 0.7, \\ -P_{\text{ctrl}}, & \text{SOC} > 0.7 \end{cases} \] (18)

3.2.2 Prosumer reactive power operation range: The reactive power range of the load is already given as a fixed demand. The reactive power behaviour of other prosumers is considered to be flexible up to the minimum power factor \( \text{pf}_{\text{min}} \). Fig. 2 shows the reactive power range for a control value \( Q_{\text{ctrl}} = 0 \). With a given control value \( P_{\text{ctrl}} \) for the active power, the absolute value of total minimum and maximum reactive power is
\[ Q = \min \left\{ \sqrt{S^2 - P_{\text{ctrl}}^2 \cdot \tan^2(\text{acos}(\text{pf}_{\text{max}}))} \right\}. \] (19)

The optimal reactive power (dotted black line in Fig. 2) is determined according to the voltage measurement value. If the voltage is low, the optimal value corresponds to a more capacitive behaviour and vice versa. To calculate the optimal reactive power value, a \( \Delta Q(v) \) approach is applied. The current value of \( Q_{\text{ctrl}} \) is increased or decreased according to the normalised voltage \( v \). The rated apparent power \( S_{\text{r}} \) is used as slope
\[ \Delta Q(v) = (v - 1) \cdot S_{\text{r}}. \] (20)

\[ Q_{\text{opt}}(v) = Q_{\text{ctrl}} + \Delta Q(v). \] (21)

The limits of the DERs are considered so that
\[ -Q_{\text{r}} \leq Q_{\text{opt}}(v) \leq Q_{\text{r}}. \] (22)

Minimum and maximum values are found so that they allow a certain range of operation while supporting voltage stabilisation. Two cases need to be considered: a normalised voltage below and above 1 pu. If the voltage is below 1 pu, the maximum value of the reactive power is adjusted to converge to \( Q_{\text{opt}}(v) \) for a decreasing voltage. The curve for \( Q_{\text{opt}}(v) \) (dark blue line in Fig. 2) is split into four parts

\[ Q_{\text{opt}}(v) = \begin{cases} Q_{\text{el}}, & v > 1, \\ Q_{\text{el}} \cdot \left(1 - \frac{1 - v}{0.025}\right), & 0.975 < v < 1, \\ Q_{\text{opt}}(v) \cdot \frac{0.975 - v}{0.05}, & 0.925 < v < 0.975, \\ Q_{\text{opt}}(v), & v < 0.925. \end{cases} \] (23)

\( Q_{\text{opt}}(v) \) starts from \( Q_{\text{el}} \) at \( v = 1 \) pu and decreases to zero for \( v = 0.975 \) pu. In the range \( 0.925 < v < 0.975 \), \( Q_{\text{opt}}(v) \) decreases towards \( Q_{\text{opt}}(v) \) so that it reaches \( Q_{\text{opt}}(v) \) at \( v = 0.925 \) pu.
The curve for $Q_{\text{opt}}(v)$ (light blue line in Fig. 2) also splits into four parts:

\[
Q_{\text{opt}}(v) = \begin{cases} 
Q_v & v < 1, \\
Q_v \left(1 - \frac{v - 1}{0.025}\right) & 1 < v < 1.025, \\
Q_v \cdot \frac{v - 1.025}{0.05} & 1.025 < v < 1.075, \\
Q_v & v > 1.075.
\end{cases}
\] (24)

If the voltage is > 1 pu, the operation range is reversed compared to $Q_{\text{opt}}(v)$.

3.2.3 Prosumer negotiation: The operation range values for active and reactive power represent the capabilities and the desired operation range of each DER. However, a simple application of optimal values does not ensure that global goals are fulfilled. Hence, agents negotiate the amount of active and reactive power they consume or produce. Active and reactive power is negotiated separately but with the same methodology. Two communication protocols are used for negotiations: Subscribe and Contract-Net. Prosumer agents distinguish between three kinds of groups of other agents: internal agents (agents located at the same node), swarm agents (agents that belong to the agent’s swarm) and the substation agent. Agents try to balance power as local as possible. Hence, a negotiation with an internal agent has a higher priority compared to one with a swarm agent. Similarly, negotiations with agents in the swarm are of higher priority than negotiations with the substation. Additionally, two cases are distinguished for negotiation of power: fixed power and flexible power. Thereby, flexibilities in power consumption and production can be considered in the negotiation.

Subscribe protocol: Consumers subscribe to producers in their swarm to receive updates on the amount of power that can be supplied. The Subscribe protocol (Fig. 3) is used for this purpose. Consumer agents subscribe to a producer which answers with an agree message and stores the subscribing consumer’s address. Then, the producer sends an inform message to all subscribed consumers whenever the amount of power that can be provided changes. Receiving consumers store the amount of power provided by producers (producer service). If a consumer no longer requires the service of a producer, it can unsubscribe and thereby triggers the producer to forget the consumer. The producer transmits three values to each subscribed consumer:

- Minimum (min): The amount of power the producer wants to supply to the grid.
- Maximum flexible (flex): The maximum amount of power the producer can offer to a flexible consumer.
- Maximum fixed (fix): The maximum amount of power the producer can offer to a fixed consumer.

Fig. 4 visualises the calculation of the producer service for a determined operation range ($P_{\text{int}}, P_{\text{opt}}$ and $P_{\text{min}}$). Note that the sign of the power is negative since it is produced. Consumers with a fixed demand can be supplied up to $P_{\text{int}}, P_{\text{opt}}$ flexible up to $P_{\text{opt}}$. Due to power generation having a negative sign, $P_{\text{int}}$ is the minimum value of active power a producer can supply. With $P_{\text{con,fix}}$ and $P_{\text{con,flex}}$ being the already contracted fixed and flexible power, the service values are calculated to

\[
\text{fix} = \left[P_{\text{min}} - P_{\text{con,fix}}\right],
\]

\[
\text{flex} = \left[P_{\text{opt}} - (P_{\text{con,fix}} + P_{\text{con,flex}})\right],
\]

\[
\text{min} = \left[P_{\text{min}} - (P_{\text{con,fix}} + P_{\text{con,flex}})\right].
\] (25) (26) (27)

For the calculation of the maximum flexible and maximum fixed service value, the producer distinguishes the different group types. Internal agents have higher priority than swarm agents, which in turn, have a higher priority than the substation agent. For

this purpose $P_{\text{con,fix/flex}}$ is calculated as the sum of all internal contracts for internal agents, as the sum of internal and swarm contracts for swarm agents and as the sum of all internal, swarm and substation contracts for substation agents.

Contract-Net protocol: The Contract-Net protocol is used for the negotiation of power (Fig. 5). It is initiated by consumers with a flexible and/or fixed power demand. For this purpose, consumers search for producers that can supply the required amount of power by using the afore-mentioned services they received from the producers. Subsequently, they send a call for proposal containing the values of the required flexible and fixed power. The contacted producer checks whether the demand can be covered and answers with a proposal the consumer can accept. Accepting the proposal means that the contract between producer and consumer is concluded. Contracts can be reduced by both partners anytime. At each time step, they check whether the contracted power can still be supplied/consumed and inform the contract partner if the contracted power has to be reduced. The negotiated values of fixed and flexible power depend on the group type of the producer. Fig. 4 shows their calculation. A consumer negotiates a fixed demand $P_{\text{fix}}$ up to $P_{\text{opt}}$ (blue solid arrow) and a flexible demand $P_{\text{flex}}$ equal to the difference $P_{\text{max}} - P_{\text{opt}}$ (blue dashed arrow) with an internal producer. Fixed demands $P_{\text{fix}}$ or sub $P_{\text{sub}}$ with a value up to $P_{\text{min}}$ are negotiated with a swarm producer and the substation, respectively (red solid arrow). Flexible demands $P_{\text{flex}}$ or sub $P_{\text{flex}}$ equal to the difference $P_{\text{opt}} - P_{\text{min}}$ are also negotiated with swarm producers and substation, respectively (red dashed arrow).

3.2.4 Control values: The negotiation of prosumers leads to a list of contracts that are concluded with other agents. The control
values of active and reactive power $P_{\text{tot}}$ and $Q_{\text{tot}}$ are calculated as the sum of all concluded contracts for fixed and flexible power. Since the negotiation of contracts is based on the operation range, the procedure ensures that the individual local goals of each agent are met. At the same time, the need to find a contract partner ensures that the global goal of power balance is met.

3.2.5 Swarm forming: Initially, agents only know internal agents and agents at neighbouring nodes. Whenever a consumer does not find a producer in its list of services that can provide enough power to cover the consumer’s demand, it asks the so-called directory facilitator (DF) for more producers. The DF is an agent without control capability. Instead, it only has knowledge about each agent’s type (consumer or producer) and the topology of the grid. The DF does not know the current state of the grid or any time variant grid or agent parameters. Both the agent types and the topology are static information that can be provided to agents if requested but not used for any kind of control decision making in the DF itself. Hence, the DF can be used to request more producers when needed. This is done using the Recruiting protocol (Fig. 6). A consumer needing more producers sends a proxy message to the DF containing the maximum distance a producer should have to the consumer. The DF searches for all producers within the specified distance and sends their addresses to the consumer with an inform message. Then, the consumer can use the Subscribe and Contract-Net protocols to interact with the new producers. The swarm of the consumer grows based on this procedure. Swarm growing is limited to a maximum swarm size. This is necessary to avoid situations in which each agent’s swarm contains all producers in the same grid as this would lead to a very high communication effort. Each time step, a consumer checks whether it has producer agents in its swarm for which no communication took place for a certain amount of time. These agents are deleted from the swarm and the consumer unsubscribes from them to not receive their producer service anymore. Shrinking the swarm is necessary to limit the total number of messages exchanged between agents. Each agent maintains its own swarm and takes care of swarm growing and shrinking if necessary. As a result, a single agent can belong to multiple swarms of other agents.

3.2.6 Substation OLTC control: For the optimal position of the OLTC, a substation considers the voltage at the primary node and the underlying grid. The voltage in the grid connected to the secondary side is determined by a distributed measurement. For this purpose, 50% of the agents in that grid are contacted by means of the Query protocol, which is used to query measurement values (Fig. 7). The substation calculates the normalised mean value of all received measurements $v_{\text{mean}}$. Moreover, it also extracts the normalised maximum and minimum value $v_{\text{max}}$ and $v_{\text{min}}$. For the optimal tap position, three cases are considered based on the normalised voltage of the primary node $v_p$:

$$\Delta n(v_p) = \begin{cases} \text{floor}\left(\frac{v_{\text{max}} - 0.9}{r} - 1\right), & v_p < 0.95, \\ \text{round}\left(\frac{v_{\text{mean}} - 1}{r} - 1\right) - 0.95, & 0.95 < v_p < 1.05, \\ \text{ceil}\left(\frac{v_{\min} - 1.1}{r} + 1\right), & v_p > 1.05. \end{cases}$$ (28)

The range in which the turns ratio can be altered is $r$ (in %) and the number of tap positions is $N$. The new tap position is found to be

$$n_{\text{new}} = n + \Delta n(v_p).$$ (29)

If the normalised voltage of the primary node is $0.95 < v_p < 1.05$, only the mean voltage value in the underlying grid is considered. That means that the turns ratio is increased if the voltage is higher than its nominal value and vice versa. In case the voltage at the primary node is outside the given range it has to be considered for the tap position. As a change of the tap position changes the voltage in the underlying grid, it also changes the reactive power range of DERs connected to that grid. This might cause a reversed operation of these DERs and could lead to an even worse voltage quality at the primary node. Hence, if the voltage quality at the primary node is considered bad, a tap position should be chosen which stimulates the DERs to show a supporting reactive power behaviour. That means the voltage quality in the underlying grid has to be worsened as much as possible regarding the minimum and maximum value of the obtained voltage measurements. For $v_p < 0.95$, the voltage in the underlying grid should be decreased so that the minimum voltage is still higher than 0.9 plus the voltage change of one tap position. If the voltage is $v_p > 1.05$, the opposite action has to be taken. The substation queries voltage measurements and calculates the tap position every 5 min.

3.3 Extension to multiple voltage levels

As already stated in Section 2.2, the concept of a holonic architecture is utilised for the extension to multiple voltage levels (see Fig. 1). The lowest layer within the hierarchy consists of prosumers located in the LV grid behaving as described in the previous section. Problems that cannot be solved within this layer, e.g. a certain power demand that cannot be covered, are forwarded to the next layer. The next layer consists of all secondary substations and prosumers located in the MV grid. Secondary substations aggregate the power that cannot be balanced within their LV grid and behave as prosumers in the MV grid. Two possible cases have to be distinguished to determine if the substation acts as a producer or consumer in the MV grid: a power lack or surplus within the LV grid. Note that while the substation represents the LV grid in the MV grid and the MV grid in the LV grid, it has no direct control capability regarding single DERs. Instead, it acts as a broker by forwarding the capabilities and needs of prosumers in one grid to prosumers in the other.

The substation is only contacted if a local adjustment of power with internal and swarm agents is impossible. It represents the primary grid in the underlying grid and vice versa. The substation subscribes to all producers in its own grid. The consumers of a grid only subscribe to the substation if they cannot find a local producer and have already reached the maximum swarm size. All components in the grid of a substation are treated as internal agents. In the following, the behaviour of a substation is explained for a secondary substation, i.e. a substation located between LV and MV grid. The same considerations are valid for the primary (HV/MV) substation.

If all DERs in a grid consume more power than they can produce, the substation has to operate as a consumer in the primary grid. It aggregates all the services it receives from producers in its swarm and from the primary substation and forwards the aggregation to the subscribed consumers in its own grid. These consumers can initiate a negotiation with the substation following the described Contract-Net protocol. The substation proposes a contract if there are enough services in its swarm to cover the demand.
Simultaneously, the substation starts a corresponding negotiation with its swarm or with the primary substation.

If the LV grid produces more power than it consumes the substation has to operate as a producer in the MV grid. It aggregates all the services it receives from internal producers and forwards the aggregation to consumers in its swarm and to the primary substation. These consumers can initiate a negotiation. The substation proposes a contract if there are enough internal services to cover the demand. Simultaneously, the substation starts a corresponding negotiation with internal producers. The substation has to ensure that the sum of all contracts with internal agents, swarm agents, and the primary substation equals zero at any time. That means the same amount of power that is contracted with internal agents has to be contracted with swarm agents or the primary substation with opposite sign.

The main motivation for this approach is a better management of communication among agents. A distribution grid consisting of LV and MV level could possibly contain several thousand prosumers with different orders of rated power at each voltage level. Allowing each agent to contact each other agent would potentially lead to chaotic communication patterns and therefore to poor scalability features. This is why in SwarmGrid-X, agents communicate only within their grid and with their substation. Thereby, communication happens only locally enhancing the scalability of SwarmGrid-X. Moreover, the holonic approach facilitates an easy extension to more voltage levels by repeating the described hierarchy at every substation. That means the same methodology is applied to the primary substation which represents the LV grid at the HV level.

### 3.4 Transmission system support

Transmission system support is an important feature of SwarmGrid-X. It allows to influence the operation of the MAS from outside and to drive the overall operation towards a global goal regarding the point of common coupling to the transmission system. Again, the holonic architecture plays a major role for the realisation of transmission system support in SwarmGrid-X. As can be seen in Fig. 1, the requirements of the transmission system can be introduced at the primary substation by means of a target value for active and reactive power. A specialised agent, called slack agent, is responsible for ensuring that the overall distribution grid behaviour coincides with the target values. To achieve this, the slack agent obtains an operation range for active and reactive power, similar to prosumer agents, with a minimum, maximum and optimal value. The slack agent only knows the primary substation agent as its internal agent. The primary substation agent aggregates demands and services of prosumer agents in the MV grid and forwards them to the slack agent. According to the operation range, the slack agent behaves like a consumer or producer and communicates with the primary substation agent using the afore mentioned protocols for service promotion and contract negotiation. To ensure that the target value for active or reactive power can be achieved, the slack agent also considers grid losses and the reactive power demand of the grid. The contracted power is compared with a power measurement and additional contracts are concluded to compensate the difference between measurement and contracts.

The determination of the operation range should be performed by a TSO that either needs the distribution grid to provide a certain reactive power for voltage support or wants to activate a certain amount of active reserve power. However, the TSO has to make sure that the operation range lies within realistic values that can be achieved by the distribution grid. To ensure this, the TSO can be supported by a rough forecast or historic data for similar conditions. In this study, we analyse the potential of a given distribution grid to support the transmission system with as much reactive power as possible.

As described above, coordination among different voltage levels includes the substation agent as a broker. This implies that more communication has to be performed by the substation agent compared to prosumer agents who negotiate with other prosumer agents only within one voltage level and subgrid. As a result, reactions of prosumer agents at one voltage level on a request from another voltage level (or even the TSO) take more time than negotiations within one voltage level or subgrid. The different reaction times can be estimated by counting the required number of messages and multiplication with communication latencies. While a single contract negotiation within one voltage level takes a minimum number of three messages (see Section 3.2.3) the alignment of the total power output of the distribution grid with the TSO request can take up to 1 min (see Section 5).

### 3.5 Congestion management

With a growing number of power generation units installed in distribution grids, line congestions become increasingly problematic for DSOs. To avoid overloading of grid equipment, these congestions have to be prevented by both grid expansion and an active congestion management. In this study, we focus on voltage control in the distribution grid and transmission system support. We understand that congestion management is an important feature for a distribution automation concept which will further extend SwarmGrid-X in the future. Note that the operation range determined by prosumers already embodies a possible solution for a decentralised congestion management. Once a congestion is detected, prosumers responsible for this congestion could adjust their operation range to reduce the stress on the overloaded line. For this work, we neglect congestions and analyse scenarios showing no congestions.

### 4 Assessment methodology

#### 4.1 Reference scenario

To have a reference system behaviour for the two scenarios defined in Sections 4.2 and 4.3, we use two respective reference simulations in which agents behave as defined in the reference scenario in [4]. In this scenario, all components behave according to currently valid guidelines in Germany. No coordinated behaviour or communication among agents takes place. Especially the components’ reactive power behaviours are much different from the one of SwarmGrid-X as generation units use a \(\cos(q)^{P}\) characteristic. A comparison to the reference scenario’s results enables the assessment of the added value of SwarmGrid-X benchmarked against the status quo.

#### 4.2 Scenario 1: active power exchange

The exchange of active power between two 400 V LV grids coupled in a 20 kV MV grid is investigated with the help of scenario 1. One of the synthetic LV grids is a rural grid with temporary generation surplus from renewable energy sources while the second LV grid is a power consuming urban grid supplying more and larger consumers compared to the rural grid, e.g. multi-family houses and EVs. Both grids have the same topology as the 177 buses grid used in [4]. Cable lengths in both LV grids vary between 10 and 40 m. The installed powers and quantities of components are listed in Table 1. The two grids are representative for LV grids that differ in their composition and hence, have the ability to support each other. Simulations are executed with a fixed time step size of 1 s for a complete day (86,400 time steps). The selected time step size implies that all messages are transmitted within 1 s.

| Table 1 | Installed powers in LV grids of scenario 1 |
|---------|-------------------------------------------|
| **Rural LV grid** | **Urban LV grid** |
| Qty | Power (capacity) | Qty | Power (capacity) |
|------|------------------|------|------------------|
| load | 175 | 204 kW | 175 | 353 kW |
| EV   | 26  | 104 kW | 35  | 195 kW |
| PV   | 35  | 390 kW | 23  | 138 kW |
| WEC  | 5   | 108 kW | 0   | 0 kW   |
| CHPP | 25  | 325 kW | 16  | 222 kW |
| HP   | 0   | 0 (0 kWh) | 14  | 387 kW (322 kWh) |
| battery | 35 | 118 kW (301 kWh) | 21 | 65 kW (166 kWh) |
For the analysis of the active power exchange, we compare the active power flows over the secondary substations and the slack for SwarmGrid-X with the slack bus power flow of the reference scenario. To show the correlation of power flow and communication interactions, we analyse the number of transmitted messages over time. Furthermore, we show how swarm sizes of rural and urban load agents can be used as a metric for the locality of power balancing.

For assessing the impact of flexible consumption and feed-in on the performance of SwarmGrid-X, we vary the capacity of thermal storages attached to HPs and the capacity of batteries from a nominal value to zero and doubled capacity. Thereby, the total fixed power demand and supply remain constant while SwarmGrid-X can use different amounts of flexibility to balance power consumption and production.

4.3 Scenario 2: reactive power set point

A synthetic distribution grid of realistic size is used to assess voltage control in the distribution system as well as the transmission system supports the ability of SwarmGrid-X. The 20 kV MV grid consists of 30 buses in three feeders of different lengths (15, 10 and 5 buses). In the first feeder, eight large WECs with a rated power of 4 are installed. The second feeder contains 4 WECs defined for scenario 1 is connected to the remaining 16 buses. In total, the grid consists of 2865 buses and 4694 DERs. To reduce complexity for the evaluation of results, only the primary substation is equipped with an OLTC. Nevertheless, SwarmGrid-X is also capable of handling secondary substations with OLTC as outlined before.

Four simulations are executed with this distribution grid. At first, the reference scenario is simulated to obtain the status quo of reactive power flow at the point of common coupling. Second, a simulation with SwarmGrid-X without any set point for reactive power at the point of common coupling is executed. In the third simulation, the set point for reactive power at the point of common coupling is set to a value which is too large to be technically feasible for the distribution system. This way, we obtain the maximum possible reactive power support for the transmission system as SwarmGrid-X will cause the distribution system to fulfill the set point as well as possible. The second and third simulations provide the lower and upper boundaries in which the distribution system can provide reactive power to the transmission system. In the fourth simulation, the reactive power set point is varied twice during the simulation time to assess the number of time steps required to adapt to a changing request of the transmission system.

The simulated time equals 9–14 h of scenario 1. Again all simulations are executed with a time step of 1 s (18,000 time steps). Besides the reactive power behaviour at the point of common coupling, voltage band violations are analysed to assess the impact of a reactive power request on the voltage quality in the distribution system. With respect to cyber interactions, the number of transmitted messages is investigated as an indicator of the level of cooperation in the distribution system.

4.4 Simulation method

For the simulation of the scenarios described in Sections 4.1–4.3, the simulation tool DistAIX is used [43]. This tool is an outcome of the same research project as the paper at hand. DistAIX enables a scalable agent-based simulation of all distribution system components and their behaviours defined in Section 3. The components are represented as agents in the DistAIX model. Their cyber-physical interactions are simulated based on the implemented behaviours so that a study of the emergent system behaviour becomes possible – even for large distribution system models.

Usually, only small-scale scenarios (e.g. [31, 32, 34]) of non-realistic size are analysed to evaluate new concepts. We assume that from the sole small-scale analysis, no general conclusions on the applicability of concepts such as SwarmGrid-X to distribution systems of realistic size can be made. The cyber-physical interactions between components and the resulting system behaviour are expected to change with the size and composition of the system under study. With DistAIX, we have chosen a simulation tool that enables large-scale studies without model or component behaviour simplifications being required.

5 Evaluation

5.1 Scenario 1: active power exchange

Scenario 1 is well suited for analysing the holonic concept of SwarmGrid-X (SwarmGrid-X is abbreviated to SG-X in all figures), even though it does not represent a realistic distribution grid. Fig. 8 shows the active power exchange with the transmission system for the reference simulation and the simulation with SwarmGrid-X. For the reference simulation, more power is produced than consumed between 9 and 14 h, leading to a positive power exchange with the transmission system (the transmission system consumes active power). All simulations with SwarmGrid-X behave similarly until this time as consumption exceeds production in both grids and the same flexibility can be utilised in all simulations. Subsequently, the power surplus is mainly stored in batteries in simulations with SwarmGrid-X. The simulation of SwarmGrid-X without batteries reveals that the majority of the power excess cannot be used within the distribution grid. HPs make use of it and fill their thermal storages leading to a power exchange with the transmission system. They switch on and off every few minutes and thereby cause a slight waviness.

The other two simulations show that battery flexibility enables to transfer the power surplus to later hours. The more flexibility is available the better this process works. Using twice of the nominal battery capacity, the power can be balanced during hours with high PV generation and EVs can be charged with that power later. This decreases the peak values of power exchange with the transmission system. The simulation of SwarmGrid-X-X without batteries reveals that the majority of the power excess cannot be used within the distribution grid. HPs make use of it and fill their thermal storages leading to a power exchange with the transmission system. They switch on and off every few minutes and thereby cause a slight waviness.

The analysis of more scenarios with a variation of HP thermal storage capacity shows that additional flexibility leads to decreased peak values at the slack and decreased total energy exchange with the transmission system. However, the results reveal that batteries are better suited for local balancing purposes. While an increase of battery capacity from 0 to 200% of nominal capacity leads to a decrease of energy exchange with the transmission system of about 17%, the same variation of thermal storage capacity attached to
HPs only decreases the power exchange by 1%. For the same battery capacity increase, the reduction of the peak power supply to the transmission system is up to 84 and 14% for increased thermal storage capacity. Consumption peak values can be reduced by 3% by means of more battery flexibility and by 1% by means of more thermal storage capacity. One reason for the large difference between the impact of batteries and HPs is that the grid under study contains more installed battery capacity than HP thermal storage capacity. Secondly, batteries are not constrained in their flexibility provision while HPs have to ensure the coverage of a building’s thermal demand. The results for varying storage capacities show that SwarmGrid-X is able to utilise available consumption and feed-in flexibilities for a local balancing of power generation and consumption without knowledge of the available flexibilities in a central place.

Fig. 10 shows the number of messages per time step, i.e. per second for the simulation of SwarmGrid-X with nominal thermal capacity and doubled battery capacity. Since the two secondary substations do not control components directly but act as brokers for components in different grids, more communication is required when DEEs in different grids adjust their operation compared to other times. This is roughly the time in which the two grids are able to adjust their active power. It highlights the strong interdependency between cyber and power interactions. The high number of messages between 6 and 18 h results from the EVs disconnecting from the LV grid. They reconnect around 17 h and increase the number of messages again.

Fig. 11 depicts the average swarm size of load agents in the rural and urban LV grids for the same simulation. The maximum swarm size is set to 20. As both grids contain the same number of loads, comparing the average swarm size of both grids embodies a good measure for the locality of power demand coverage. Since the overall power production in the rural grid exceeds the production in the urban grid, the average swarm size in the rural grid is smaller at all times. Furthermore, the power surplus in the rural grid between 7 and 18 h leads to a decreased swarm size of loads in this grid. This means loads are able to cover their power demand with local prosumers. However, in the urban grid consumption exceeds production at all times. As a result, the swarm size does not decrease by the same amount during the same period. At 14 h, the power consumption of the urban grid reaches a minimum. Hence, the swarm size slightly decreases as a higher share of power consumption can be covered locally.

5.2 Scenario 2: reactive power set point

Scenario 2 is used to analyse voltage control in a realistic distribution grid and to demonstrate the capability of supporting the transmission system with reactive power. Fig. 12 depicts the active and reactive power exchange at the slack node for the reference simulation and SwarmGrid-X. The power exchange is shown from the point of view of the transmission system, meaning that a positive value coincides with a power surplus in the distribution system. Due to the high power production of WECs, active power is supplied to the transmission system during the complete simulation time. A local adjustment is not possible as the power generation heavily exceeds the consumption. Note, however, that for SwarmGrid-X the peak value of active power exchange is slightly decreased compared to the reference simulation, which is caused by the usage of flexible consumers.

Fig. 12 also shows the inductive behaviour of generation units in the reference simulation induced by the $\cos(\phi)(P)$ characteristic. The transmission system has to supply an enormous amount of reactive power to the distribution grid for the reference case. Fig. 13 shows the minimum, maximum, and mean values of the normalised voltage in the grid at every time step regarding all LV and MV buses. In the reference simulation, the OLTC of the primary substation changes the tap position after 2 h, increasing the voltage in the grid. This leads to a violation of the upper voltage range around the nominal value. However, not changing the tap position would have led to a violation of the lower voltage band around 3 h. WECs lead to an increased voltage in the first feeder while industrial consumers decrease voltage in the second feeder. As the voltage range is too wide, voltage band violations cannot be prevented by means of a tap adjustment alone.

The first simulation with SwarmGrid-X is executed without any target set point for reactive power exchange with the transmission system.
system. The resulting reactive power curve as shown in Fig. 12 indicates that the distribution grid still requires reactive power supply by the transmission system. However, the reactive power demand is strongly decreased compared to the reference simulation. Analysing the voltage in Fig. 13 reveals that no voltage band violations occur during the simulated time. The voltage range, i.e. the difference between the maximum and minimum value is narrowed, allowing a safe grid operation even without usage of the OLTC at the primary substation. The first simulation with SwarmGrid-X shows that the reactive power demand can be reduced while improving the voltage quality at the same time.

The following simulations reveal that an additional reactive power support of the transmission system is possible. The first step is to obtain the reactive power boundaries. For this purpose, the slack agent tries to obtain as much reactive power as possible from the distribution grid. The resulting reactive power curve is depicted in Fig. 12. During the first 2 h, a reversed reactive power behaviour can be achieved, meaning that the distribution grid supplies reactive power to the transmission system instead of consuming it. At times with high active power generation, a reversed operation is not possible due to the active power generation increasing the voltage in the distribution grid. To comply with the voltage band, generation units have to behave indirectly by consuming reactive power. However, the reactive power demand is further decreased compared to the simulation with SwarmGrid-X without a reactive power set point. Fig. 13 indicates that the voltage range is increased compared to the simulation without reactive power set point. However, all bus voltages are still within the allowed voltage band at all times.

In a second step, a target value for reactive power is applied to the slack agent. The target value is altered twice during the simulation. It is chosen in such a way that it lies between the curve of the simulation without a target value and the curve for maximum reactive power. In the beginning, the target value is 0 MVar. At time step 1000 s, the value is changed to 1 MVar. It is changed again at 7000 s to -3 MVar. The resulting reactive power is depicted in Fig. 12. In the beginning, SwarmGrid-X requires some time to fulfill the target value due to a necessary change of the OLTC position. After 5 min, the target of 0 MVar is reached and kept with a maximum deviation of 0.04 MVar. It takes <60 time steps to reach the target value after its first change. The largest deviation of about 30% of the target value occurs around time step 3500 s. However, SwarmGrid-X is able to recover from that deviation within 60 time steps. Similarly, the last set point is maintained as well. The largest deviation is about 15% of the target value. All deviations >5% can be recovered within 60 time steps (1 min). An increasing deviation can be observed at the end of the simulation. This happens due to a different tap position compared to the simulation without a reactive power target. As a result, it is not possible to maintain reactive power at the desired value. The OLTC position is not directly responsive to the reactive power target value. An improved coordination will be necessary to trigger a tap change and enable the distribution grid to reach the requested reactive power value.

In Fig. 14, the number of messages per time step for the simulation without a target value is shown. The number of messages decreases from the beginning until 3 h and increases again afterwards. Active and reactive power reaches their peak values at the time with minimum communication occurrence. Consequently, the operation of DERs has the lowest flexibility and the amount of exchanged messages is reduced because no flexibilities can be contracted. At times with more operational flexibility more communication occurs.

5.3 Communication scalability

For a scenario with \( n \) nodes, the number of possible communication links is \( n^2 \). In scenario 1, 7% of all possible communication links are utilised. Regarding scenario 2, only 0.5% of all possible communication links are used. This represents a good indicator for the communication-wise scalability of the CPPS. Local swarms lead to local communication patterns. Moreover, the amount of messages does not exceed capabilities of today’s communication technologies. Considering the total number of messages, each agent sends one message every 30 s on average. As the central aggregation of information and overall system state estimation are not required, communication bottlenecks and single points of failure are avoided. An extension of SwarmGrid-X to higher voltage levels than discussed here is intuitive due to its holonic architecture. Given that the number of messages over time for scenario 2 is in a technically feasible range for future information and communication technology systems, the inclusion of higher voltage levels in SwarmGrid-X, i.e. the coordination among distribution grids connected to the same HV grid, seems possible without scalability problems.

6 Conclusion and outlook

In this work, the authors present SwarmGrid-X, a completely decentralised agent-based distribution grid control approach capable of maintaining the voltage in the grid and complying with TSO active and reactive power requirements. All components coordinate autonomously without any form of central controller. Communication occurs only locally and multiple voltage levels interact by means of a holonic approach. As a result, no DER agent has a global system knowledge but obtains its limited view solely through communication with other agents. Thereby, SwarmGrid-X represents a large CPPS with strong interdependencies between power flow and communication. Results show that set point changes of the requested reactive power at the point of common coupling can be applied within <60 time steps. The communication effort of SwarmGrid-X is small compared to the number of components in the grid, indicating excellent scalability properties. Due to this and the holonic architecture of the concept, its extension to higher voltage levels is intuitive.

In future work, the concept can be further extended by congestion management as this is a major concern of DSOs besides voltage and violations steps. Similarly, the last set point can be communicated. Further, the communication effort of SwarmGrid-X is small compared to the number of components in the grid, indicating excellent scalability properties.
willingness to offer operational flexibilities, e.g. by means of financial incentives, can be included in the future. The authors identify possible links in the concept to incorporate these extensions in SwarmGrid-X.

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8 References

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