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***Abstract*—The operation of the distribution network will change in the near future due to increasing size and number of distributed energy resources (DER) and demand side resources (DSR). An active distribution network is proposed to address the challenges. The normal operation of an active distribution network requires coordination of different values and operation constraints of various involved actors. This paper proposes a multilevel coordination strategy for congestion management of distribution network. Firstly, the scheme of an active distribution network is described. Then, the coordination strategies between various actors, i.e., distribution system operator (DSO), fleet operators (FO), and EV owners are discussed. Further, a mathematical formulation of the chosen coordination strategies between DSO and FOs are presented and some case studies are shown to illustrate the effectiveness of the proposed solutions. Finally, we give the argument and proposal of using multi-agent based platform to demonstrate the multilevel coordination solution.**

***Index Terms*—Congestion management, Distribution grid, Multilevel coordination, Multiagent systems based platform**

I. INTRODUCTION

Denmark was a pioneer in wind power which provides a large amount of electricity to Danish consumers, at the end of 2012 [1], the total installed wind capacity in the Danish power gird was 4,162 MW which share 30% of the domestic electricity usage. Wind energy in Denmark is expected to grow due to the political strategy of 50% wind power in the 2020 Danish power system [2]. The total installed wind power in Denmark is connected at the distribution system level, which bring challenges to Energinet (TSO of Denmark). Energinet has limited or no access to the information about the state at the low grid voltage level. In order to address the challenges, several actions [3] have been implemented or planned, such as

- Coordinate the power flows among different systems by electrical interconnections, mostly high voltage direct current to the TSOs in the Sweden, Norway, Germany, and soon the Netherland.
- Balance the power system by the deregulated power market with the collaborations of power Balance Responsible Parties (BRP). The BRPs make the power and energy bids into the market, consists of conventional power and wind power.
- Implement a tool that provides real time estimation of the amount of injections from wind energy.
- Manage the flexible demand, like electric vehicles, heat pumps.

With the expected development towards a power system depentent on intermittent renewable energy sources, the need for some of the ancillary services is likely to increase, especially for balancing purposes. Both EVs and heat pumps are believed to play important roles in balancing the system. In order to aggregate the flexibilities of demand and capturing the business opportunities of providing the service to the system operator, a new business entity, namely fleet operator (FO) has recently emerged [4], [5]. Alternative names for an FO are virtual power plant (VPP), aggregator or charging service provider. However, the operation of the distribution grid may be challenged due to the increasing size and number of consumption units which can cause problems in peak hours. Besides, there exists facts that the closer the renewable production installed to the consumer premises and the consumer's awareness of consumption. As a result, the DSO have started to recognize the necessity for electricity distribution and operation evolving from the usual passive unidirectional flow network to an active distribution network [6].

In this paper, we consider a particular case combining EV charging cost minimization and distribution grid capacity management (active power transfer capacity). Previous studies [7]–[9] has shown that EVs can provide valuable services to the system operator, for example, during strong wind conditions, where the total wind power production capability becomes highly utilized, the need of maintaining balance between production and consumption might increase and can be provided by utilizing the controllable flexibilities of EVs. As a consequence the distribution system might become overloaded. Besides, the spot electricity price might become cheap when the wind power penetration is high. This will also further increase the consumption on the distribution grid side. In order to address the challenge, our study aims to answer how the values and operation constraints among the DSO, FOs and EVs can be coordinated within a market based platform sitting in an active distribution network.

The remainder of the paper is organized as follows: In section II, a general introduction regarding the operation of distribution network today and an active distribution network is given. Besides, the scheme of an active distribution network is also presented. Section III mainly presents the coordination strategies between DSO and FOs, FOs and EV owners. Then a framework for design and method development for multilevel coordination is illustrated in section IV. A case study is given in section V to demonstrate the proposed method. Further, the proposal of using Multi-Agent Based Platform to demonstrate the multilevel active distribution systems are made in section VI. Finally, discussion and conclusions are made in section VII.

II. MULTI ACTOR SETTING, MULTILEVEL COORDINATION IN AN ACTIVE DISTRIBUTION NETWORK

A. *Distribution network operation*

1) Distribution Network Operation Today: DSO tasks in conventional system operation [10], are mostly focused on ‘off-line’ tasks related to asset management and maintenance during normal system conditions. The primary objective under emergency conditions is to organize restoration of the network as quickly as possible. Distribution systems today tend to be weakly monitored as compared to transmission grids, and controlled in a decentralized fashion on the basis of preconfigured local controls (e.g. by means of grid codes and protection settings).

The key operations of the DSO are:

- Grid dimensioning (incl. contigency planning and load curve estimation)
- Maintenance and outage related topology reconfiguration
- Adjustment of transformer taps
- Fuses and relay operation
- Fault-analysis and repair
- Logging events and standard management report
- Managing trouble call information and inform customers.

2) Operation in an active distribution network: To illustrate a future operation scenario with a higher level of automation, it is considered how the above operations can be extended with additional online- and data intensive acquisition. In order to identify and solve congestion problems, the DSO requires additional measurement equipment and/or technology enabling identification and anticipation of load patterns and grid ‘bottlenecks’.

Key Operations for DSO congestion management in an active distribution network would be:

- Demand forecasting
- Grid state estimation
- Online grid measurements
- Real-time intervention in case of unexpected deviations challenging grid reliability
- Meter data collection and aggregation

B. *The scheme of an active distribution network with multi-actors, multilevel coordination*

Fig. 1 shows the scheme of an active distribution network, in which four types of actors are loaded on different levels. In general, each of the actors is associated with a kind of operations, namely, the DSO is responsible for the reliability of the distribution network, FOs are responsible for making the energy schedules, biding it into traditional market such as day-ahead spot market and regulation market and providing the electricity for end users, EV owners are taking care of the charging of their EVs by subscribing to an FO or making the charging decision by themselves. By introducing a market based platform on the distribution grid level, the DSO will coordinate their requirements with market operator who then interact with FOs. About the control/coordination relations between FOs and EVs, this could be implemented either in direct control or indirect control method. Further discussion regarding the multilevel coordinations will be presented in next section.

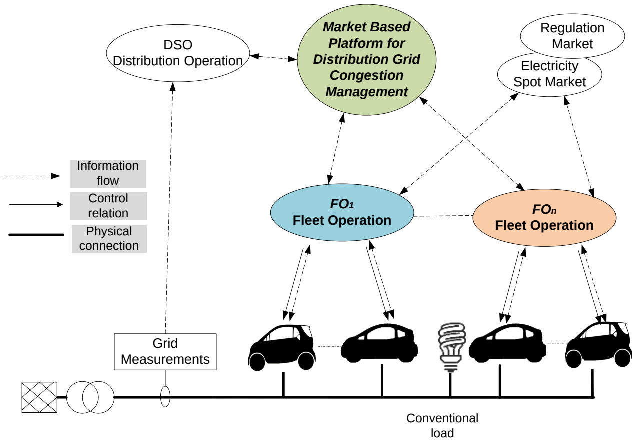

Fig. 1. Actors (stakeholders), problem domain and main information and control flows within an active distribution network.

III. COORDINATION METHOD AMONG THE VARIOUS LEVELS OF THE ACTIVE DISTRIBUTION SYSTEMS

A. *Coordination method between DSO and FOs*

Generally, the market based platform will be used to coordinate the requirements and values of DSO and FOs. The mechanism behind the market could be designed in many ways, such as various potential tariff regimes [11] [12], uniform price auction mechanism [13], shadow price based mechanism [14]. We briefly introduce three types of mechanisms in the below:

1) Dynamical grid tariff: In this method [12], the DSO generates a time and grid-location dependent price for grid usage based on expected nodal consumption levels. The DSO anticipates the size and the price-responsiveness of the load at critical grid nodes and calculates the price to optimally reflect the expected congestion problem. The FO will then get the dynamic nodal tariff and make an optimal schedule with respect to the predicted spot price and dynamic grid tariff.

2) Uniform price auction mechanism : The uniform price auction [13] can be designed as either single-sided auctions or two sided auctions. This will fully depends on the scale of the market, i.e., whether it is used by single DSO or multi DSOs supposing there are several FOs. It is noted that the uniform price auction mechanism is usually combined with optimal power flow calculation, which mean either market operator/DSO will implement a lot of calculations.

3) Shadow price based mechanism: In this method [14], FOs will submit power requests to DSO for their aggregated energy/power schedule on each node (aggregated capacity) before submitting the energy schedule to the day-ahead market; in response they will receive a price for each node which reflects the respective congestion, and are requested to update their energy schedules. The process will terminate when all constraints are satisfied.

B. Coordination method between FOs and EV owners

Research in [15], [16] give a comprehensive review on the control strategies for flexibility aggregation. Three control architectures are examined and compared in [15], namely centralized load control, hierarchical load control via aggregators and distributed control. The control method is also discussed in [15], in which direct control and indirect control in the form of price signal are described. Direct control means that FO can direct schedule and control the charging of EVs [17]. Indirect control implies that FO coordinate the charging of EVs by either two way [18], [19] or one side price signals [20]. EV owner determine the charging profile of EVs by themselves. A short comparison between direct control and indirect control is given in Fig. 2.

	Control polices	
	Direct control	**Indirect control**
Features of the control policies	• Control signals • High level controller make the decision	• Price incentive • Consumers make decision
Advantages	• High certainty • Better optimal results	• Privacy improved • Less communication cost
Disadvantages	• Sophisticated hardware • High communication cost	• Lower certainty • Demand Price elasticity is required

Fig. 2. Comparison between direct control and indirect control strategy

IV. FRAMEWORK DESIGN AND METHOD DEVELOPMENT FOR MULTILEVEL COORDINATION

Within the assumed system architecture, we propose a framework consisting of four fundamental stages [21], i.e., offline scheduling, online scheduling, real time control and settlement, to operate and control this system. These principles are in line with the system control function required at the control center of power system operation [10], i.e., instantaneous operation, operation planning and operation reporting. This framework is a fully charging profile management considering charging cost minimization and distribution grid capacity management. During the framework, shadow price based mechanism designed for the market and direct control between FOs and EV charging are used.

A. Framework design and method development for multilevel coordination

1) *Energy schedule of the FOs without congestion management-Offline scheduling*
   All the FOs need to predict the energy requirements (driving patterns) of their customers (EV owners) and plan the corresponding expected charging schedule for the EVs. The methods of estimating the energy requirements and setting up the charging schedule may be different, but in general, the FOs try to minimize the charging cost of their customers as well as guarantee the driving requirements of the EV owners.
2) *Market based approach for distribution grid congestion management-Offline scheduling*
   The market based platform will be used if congestion happens and the shadow price based mechanism is chosen for the market operation. FOs trade the power capacity of the distribution grid in this market. During the negotiation of the market, a shadow price will be issued by the market operator in the time slot where congestion happens. Then this shadow price will be sent to FOs, FOs will send back a new schedule to the Market operator, such iteration will be terminated until the congestion is eliminated.
3) *Online scheduling and Real time control*
   It is valuable for FOs to utilize the online scheduling stage and make better charging schemes, especially regarding the participation in the regulating power market. Besides, if more accurate information is provided to the FOs, FOs can judge whether they need to reschedule the charging plan during this stage. With regard to real time control, one can assume that the EVs will charge according to the plan; however, if grid normal technical operation is compromised, FO management can be overridden by the DSO operation, such as using load shedding scheme.
4) *Settlements* The settlements need to be designed well considering both the spot price and shadow prices. Besides, tax, transmission and distribution fees etc., should be taken into account.

B. Market based approach for distribution grid congestion management

In this subsection, we mainly focus on introducing the shadow price, where it comes from, how it can be utilized in the study.

1) Analytical analysis of shadow price based market operation: In general, the method starts with a proposed cost function which represents the cost of the power preference difference of a FO in each time slot, e.g.,

$$\mu_k = \zeta_k(\tilde{P}_{k,i}).$$

To facilitate the understanding, we assume

$$\mu_k = C_{k,i}(\tilde{P}_{k,i} - P^E_{k,i})^2, \tag{1}$$

where k, i denote the index for the number of FOs and time slot in the scheduling period, $k = 1, ..., N_B, i = 1, ..., N_T$

$P_{k,i}^{E}$ means the schedule planned by FOs, $\tilde{P}_{k,i}$ denotes the control variable, $C_{k,i}$ means the weighting factor which are associated with the power difference, the larger $C_{k,i}$ implies a smaller difference.

The objective is to minimize the cost functions as well as respect to the constraint from DSO:

$$minimize \quad \sum_{k=1}^{N_B}\sum_{i=1}^{N_T} C_{k,i}(\tilde{P}_{k,i} - P_{k,i}^{E})^2$$

subject to

$$\sum_{k=1}^{N_B} \tilde{P}_{k,i} \leq P_{Cap}(i), i = 1, ..., N_T, \tag{2}$$

where $P_{Cap}(i)$ is the power capacity specifically for all the FOs, for example, it can be estimated by the DSO after deducting the conventional loads.

This problem is a convex optimization problem and relevant research [22], [23] show that by introducing Lagrange multipliers or shadow price $\Lambda(i) \in R^{N_T}$, problem (2) can be transferred into following partial Lagrangian problem:

$$L = \sum_{k=1}^{N_B}\sum_{i=1}^{N_T} C_{k,i}(\tilde{P}_{k,i} - P_{k,i}^{E})^2 + \sum_{i=1}^{N_T} \Lambda(i)(\sum_{k=1}^{N_B} \tilde{P}_{k,i} - P_{Cap}(i)) \tag{3}$$

.

The centralized optimization problem (2) is transferred into a decentralized one with associated shadow price $\Lambda(i)$ in each time slot, with the purpose of emulating the market behavior. In our previous study [24], a strict mathematical proof is presented for the justification of the shadow price based mechanism.

2) Cost and schedule adjustment algorithm within the market based platform: The following steps illustrate the interactions among DSO, FOs, and market operator, cost adjustment algorithm and can mimic the trading and negotiation process in the market operation, when congestion happens.

(1) FOs submit their energy schedule to the DSO before submitting them to the electricity spot market.

(2) The DSO predicts whether congestion will happens based on the schedules of FOs, if happens, FOs need to go to the capacity market, otherwise, the energy schedule is approved.

(3) Capacity market operation

- FOs send their power schedule $P_{k,i}^{E}$ to market operator.
- Market operator determines the shadow price $\Lambda(i)$ and sends the price to FOs.
- FOs update their power schedule according to the shadow price and send it again to market operator.
- Such iteration will be terminated according to certain criteria, e.g., price convergence.

Intuitively, Fig. 3 illustrate the operation sequence.

V. NUMERICAL EXAMPLES

In this step, we will illustrate the effectiveness of utilizing the shadow price, i.e., $\Lambda(i)$ to facilitate the congestion management in the proposed method. It is noted that the cost function in this study presented by the quadratic function is assumed to represent the cost for the energy preference loss. The accuracy of the cost function is out of the scope of this study, the focus is to show how the FOs establish the schedule based on the cost function and the shadow price.

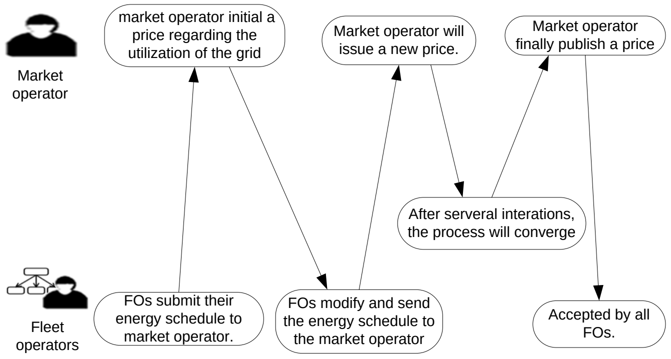

Fig. 3. Convergence of $\Lambda(i), i = 9, 10, ..., 16$ toward the shadow price.

The weighting factor rate $C_{1,i}, C_{2,i}$ is set to 0.5 and 0.1. The value of α_ω is chosen as 0.1 in this case. Note that the variable $C_{k,i}$ and α_ω are connected, an appropriate value of the two variables can ensure smooth operation of the proposed method, i.e., the trade-off of the speed of the convergence and the accuracy of the solution. However, there is not a strict rule for choosing the parameter values. The power capacity $P_{cap}(i)$ is set up according to the trend in the real case; generally, the capacity is higher in the later evening and early morning time and lower in the day and evening time. Fig. 4 is presented to note the convergent process of the shadow price. During the time slot of 9 to 16 (15 minutes based time slot in a 24 hours time window), there exists congestion in the network, the total power demands from FO_1 and FO_2 are same in these time slot, (i.e., 39.1 kw from FO_1 and 41.4 kw from FO_2), but the capacity reserved for these time slot is 70kW. The result shows that the steady state is reached quickly. Note that each FO will obtain the final power schedule after the market operation. Because of page limitation, FO1's example is shown here, as presented in Fig. 5. From Fig. 5, one can see that the newly obtained power, i.e., the green curve is quite close to the blue curve, this is because FO_1 have higher weighting factor rate, which further imply that FO_2 will need to reduce a little more power comparing to FO_1.

VI. GRID CONGESTION MANAGEMENT WITHIN A MULTI-AGENT SYSTEMS BASED PLATFORM

In the discussions above, it is observed that some general design principles are used such as decomposition, abstraction and scalability. These principles match the inherent capabilities of software agents and multiagent systems. In fact, multiagent system have been widely considered for control of power systems [25], starting from a low level control of devices to higher level of planning and optimization. A detailed explanation for the application of the three principles mentioned above

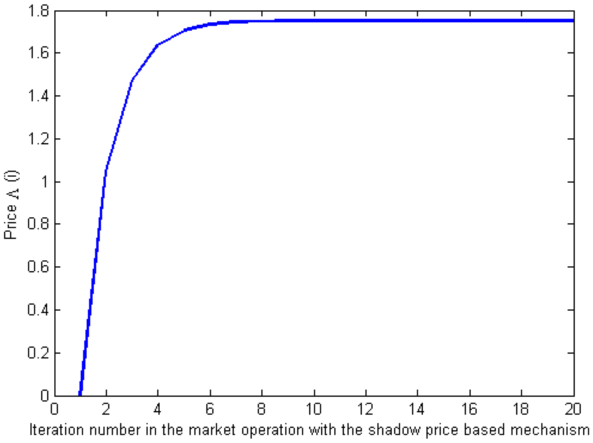

Fig. 4. Convergence of $\Lambda(i), i = 9, 10, ..., 16$ toward the shadow price.

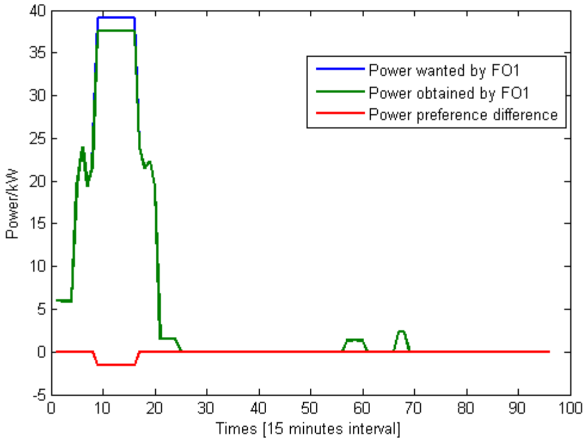

Fig. 5. Convergence of $\Lambda(i), i = 9, 10, ..., 16$ toward the shadow price.

is presented below:

- Decomposition: The electricity supply for the ender users is provided by several FOs. The congestion problems in a distribution network can be decomposed into subproblems, which the different DSO may face challenges on different levels of their grid. Some DSO might foresee problems on the medium voltage grid, while others may encounter potential problems with capacity in the low voltage transformers.
- Abstraction: Abstraction can be used to define a simplified model of the system that emphasizes some of the details or and suppresses others and to organize network operation. In this study, for example, FOs can be used to abstract the requirements and operations constraint of EV owners. In addition, the radial distribution grid can be abstracted in the form of Fig. 1 when emphasizing the active power transfer capacity management.
- Scalability: Multiagent systems have mature mechanism for implementation of cooperative and competitive mechanisms. These mechanism can be used in the interaction of the market operator and the FOs. We will consider some competitive mechanisms between FOs in a future study because the above case studies mainly illustrate how the FOs can cooperate to mitigate the grid congestion problems.

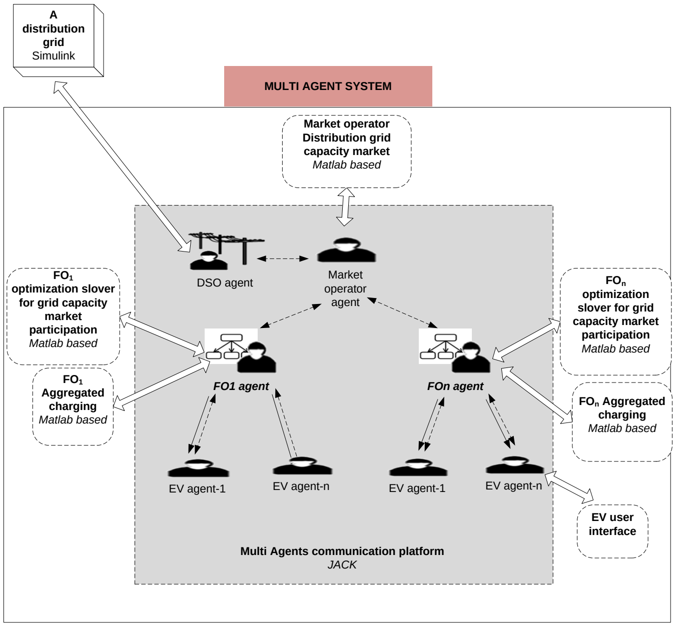

Fig. 6. Multiagent system based realization of the proposed scheme of an active power distribution network

According to the arguments above, we propose a multi-agent system architecture for the realization of the coordination of an active distribution network with multi-actors, as presented in Fig. 6. In which, all the agents will be built on JACK which is an agent-oriented development environment built on top of and fully integrated with the Java programming language [26]. JACK offers the environment and facilities message sending/receiving. Matlab based functions enables a declarative implementation of the decision module. Fig. 7 shows the skeleton of the agents in the JACK platform, in which three agents are presented, i.e., FO agent, DSO agent, Marketoperator agent. The envelope box represents the event that will be transferred between the agent. The rounded rectangle box means the plan that each agent has which will be used to handle the events. Basically, this skeleton illustrates the interactions between three agents intuitively.

VII. CONCLUSION

This paper primarily propose a framework for coordinating the values and operation constraints of various actors in an active distribution network. Multilevel coordination strategies are used in this study, i.e., price based platform is used to solve the congestion problems between DSO and FOs and direct control method are adopted to control the charging of EVs by FOs. We further give an argument that multi-agent based platform is suitable for the demonstration of the active distribution network with multi-actor setting, multilevel coordinations. A

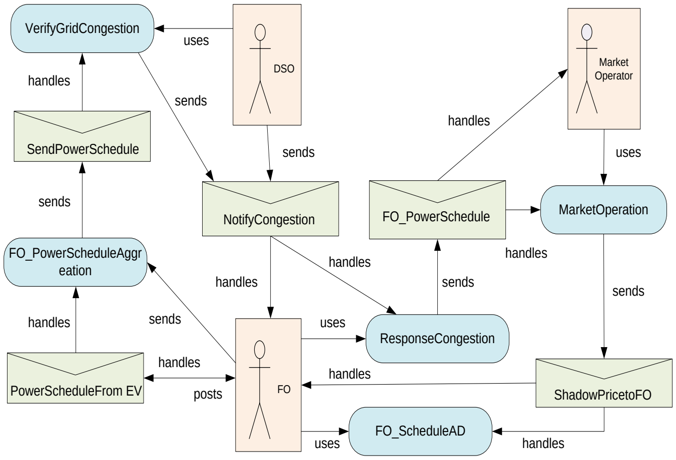

Fig. 7. Design view of the multi-agent systems in the JACK

scheme of the multi-agent system is presented. It is believed that we are able to show the interactions between different agents in an easier way by using multi-agent technology. Also, it is easier for software development. More than this, we want to show the scalability of expanding the system into a level where agents sit in different place, this could demonstrate more realistic case.

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