MULTI-AGENT-BASED GRID AUTOMATION: FIELD TEST EXPERIENCES OF THE DISTRIBUTED GRID STATE CONTROL

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ABSTRACT

This contribution presents the field test experiences and results from a multi-agent-based grid state control in a real low voltage distribution grid. Specific scenarios of grid state violations (capacity overload and lower voltage violation) are generated to show, how decentralized agents collectively find a control decision using an agent-based negotiation protocol.

INTRODUCTION

Grid automation systems are increasingly used in German distribution grids as an intelligent response to the challenges of the German energy transition [1]. In particular, the main challenge is to cope with the upcoming large-scale integration of distributed renewable energy resources, which results in a more and more complex optimization problem with increasing system size [2]. The current vertical control approach of using a centralized Supervisory Control and Data Acquisition (SCADA) system has deficiencies in flexibility and adaptability, therefore it is no longer sufficient for certain control operations [3]. New plants have to be integrated into the system, which will lead to longer system reaction times so that conventional omnipotent problem solvers cannot be applied anymore. In addition, a single fault can lead to effects affecting power supply and quality [4]. The question arises why the structure of a grid automation system cannot be decentralized like its feeders and loads. As a possible solution, Multi-Agent-Based Grid Automation Systems (MAB-GAS) are mentioned [5]. This contribution is a continuation of the previous work on MAB-GAS [6] and deals with the concept of the agent-based grid control in real distribution grids. The gained experiences from the performed field test are presented and discussed in this contribution. The focus of the investigation is on decentralized organization and determination of control decisions based on multiple distributed agents in the field. Here, a superordinate agent, which is able to identify cable overloads or voltage band violations, monitors an assigned grid. In case of grid violations, the problems will be classified according to their urgency; the worst problem will take precedence. The superordinate agent does not solve the problem itself, but rather together with other agents in the field by opening an auction. All participant agents in this auction will receive the problem and thus each participant can offer possible solutions based on its own local objectives and its models.Section 2 describes the foundation and the implementation of the agent-based GAS. The third section shows the concept of the agent-based control. In the fourth section, the results of the agent-based control are shown. Section 5 deals with the critical analysis of the implemented approach. Section six summarizes the results and experiences of the agent-based grid state control in a practical field application under real conditions.

CONSTRUCTION OF AN AGENT-BASED GRID AUTOMATION IN THE FIELD AREA

The agent-based GAS was tested in a real low distribution grid in North-Rhine-Westphalia, which is schematically shown in figure 1.

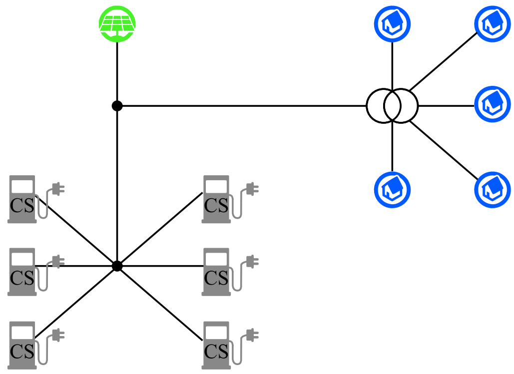

Figure 1: Part of the real low distribution grid for the field test

The real distribution grid consists of six charging stations (CS) for electric vehicles, a 113kWp photovoltaic plant (green node) and five conventional loads (blue nodes). In this study, each cable sections are measured for an optimal display of the current grid state. The photovoltaic plant and the charging stations are controllable. It is possible to change the apparent power S and the power factor $\cos(\varphi)$ of the actuators. The logging of the measurement data and the control from the GAS to the actuators are realized via the standardized Modbus TCP protocol. In addition to the hardware structure, the agent-based GAS must be developed. For this purpose the development platform "Agent.Workbench" [7] was utilized, which was developed by the University of Duisburg-Essen. On this platform all types of agents were modeled and represent in this context "energy agents". Figure 2 shows the structure of an energy agent, that contains a domain model as well as a simulated and real interface.

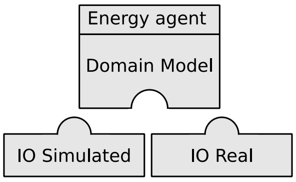

Figure 2: Structure of an energy agent

As shown in Figure 2 an energy agent for example a sensor agent has a simulated interface that generates measurement values from the grid simulation. These measurement data is processed and evaluated in the domain model. In the case of a real field usage the real interface is used. The real interface establishes a communication via Modbus TCP and passes the real measurement data to the domain model in the same way as the simulation mode. Summarizing, the domain-oriented model of the energy agent does not see the difference between the real and simulated use. In a similar way, the interface for the agents of the charging stations is developed. The domain model of the charging station will send set point values via the interface. In the real usage, the set point will be also forwarded to the charging station via Modbus TCP. The domain model of the charging station includes the information about the current state of the electric car and the information about possible control set points.
Every agent is modeled and created on a central operating PC, which can be situated at the distribution system operator (DSO). In the course of the field test, the operating PC can be found at the institute of power system engineering of the University of Wuppertal. However, the question arises how the centrally created agents can be deployed decentral in the field. For this purpose a deployment routine was built, which makes it possible to load agents directly onto the right field hardware.The chosen field hardware units are conventional industrial PCs, which are equipped with a Linux operating system and a Java Development Kit (JDK). In figure 3 the installed industrial PCs are shown. For reason of easier field implementation, all industrial PCs are located in one cable cabinet, but all PCs work as if they were distributed in the field. Each industrial PC is connected to a physical sensor and receives measurement data. The charging stations can be controlled by the industrial PCs.

Figure 3: Photo of the installed hardware in a cable cabinet

AGENT-BASED CONTROL

Characteristic for an agent-based control is the cooperative development of control decisions. Each agent has different local objectives and a different view on global problems. The idea of the agent-based control can be illustrated in detail in the implementation of the field test. The current grid state is identified by a decentralized agent called District Agent. This District Agent receives measurement data from Sensor Agents via an agent subscription mechanism [6]. On the basis of the measurement data, the grid state is identified and evaluated. In case of a grid state violation, the District Agent starts a control operation. The control algorithm identifies the intensity of the grid state violation and initiates either a yellow or red traffic light phase. In the following, the yellow and red traffic light phase are explained.
In case of the yellow traffic light phase a protocol called Contract Net Protocol (CNP) is started. This protocol represents an approach for a distributed problem solving mechanism and can be divided into four phases: recognition, announcement, bidding and awarding [8]. In the recognition phase, the agent recognizes that the agent cannot solve the problem itself and creates a specification to describe the problem in the second phase. After the other agents have received the announcement, the agents decide whether they are able to solve the problem or not. If a solution was found, they make a bid for solving the problem.
In the following the CNP is explained in the context of the GAS. In the yellow traffic light phase the District agent accesses its network model and determines all actuators. Subsequently, the actuator agents are informed about the current grid state problem (upper or lower voltage range violation or capacity overload) and requested to participate in solving the problem. The Actuator Agent does not know the network topology, the location and the quantitative extent of the problem. However, the actuators must develop possible solutions on the basis of the received qualitative message. Local

objectives and technical restrictions of the actuator are taken account in finding solutions. The actuator creates several solution proposals in the form of a list sorted in descending order of preference. The first entry of the list represents the preferred power adjustment with the lowest reduction of local objectives. This proposal list is transmitted and evaluated by the District Agent. Using sensitivity analyses [9+10], the District Agent can determine the actuators with the highest influence on the violated grid state. The District Agent calculates the grid state with the power proposals of the actuators until the critical grid state can be fixed. If a solution has been found, the respective actuators are notified about the control decision. Finally, the grid state is corrected and the behavior is terminated. The red phase occurs, when an abrupt critical grid state occurs, which have to be resolved immediately. A negotiation as in the yellow phase would take too long time and therefore a different control strategy for the red phase was developed. In this phase, the District Agent executes a sensitivity analysis to select directly the actuator with the highest influence for solving the grid state problem. The District Agent calculates the quantitative power adjustment and sends this desired set point directly to the actuator. The received set point would not fit exactly, because the District Agent does not have the knowledge about the technical system of the actuator. However, the Actuator Agent has its own technical system and can choose a set point that is most similar to the desired set point of the District Agent. After the set point has been set, the actuator agent sends a confirmation with the selected set point back to the District Agent. Finally, the District Agents checks the new grid state and exits the behavior. In summary, two different control strategies were presented in this chapter. Each agent has only a limited knowledge and view on the problem. The agent-based cooperation and negotiation is designed to find an optimal solution in each case as long as control capacity is available in the network.

RESULTS OF THE AGENT-BASED CONTROL IN THE FIELD TEST

The previously presented control strategies were examined in the field test. Figure 4 shows the first test.

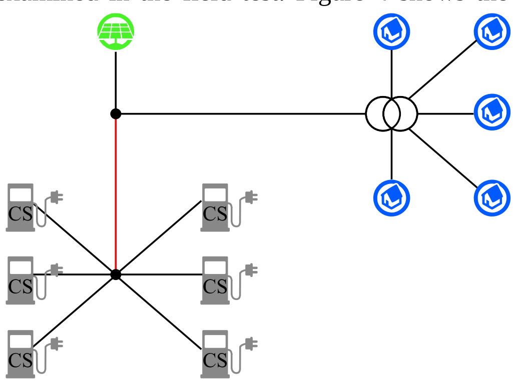

Figure 4: First field test scenario: Cable overload

As shown in figure 4 the capacity overload is situated between the photovoltaic plant and the pool of the charging stations (red colored cable). The photovoltaic plant in yellow feeds in and all charging stations are used with a maximum of load. The fuse of the transformer is not able to detect the cable overload, because the powerflow flows directly from the photovoltaic plant to the charging stations. The GAS is able to detect the grid state violation and starts the yellow traffic light phase. Now, the District Agent starts the CNP to distribute the solving of the problem. The charging stations continue to pursue a user-oriented loading behavior and offer solutions that do not violate the loading objective of the electric vehicle. In the finding of a solution proposal, the state of charge, the battery capacity and the desired departure time are taken into account. In this test, only different departure times were set for the charging station agents, so the charging station with the longest loading time is limited first. In figure 5 the measured grid state and the actuator set point is shown.

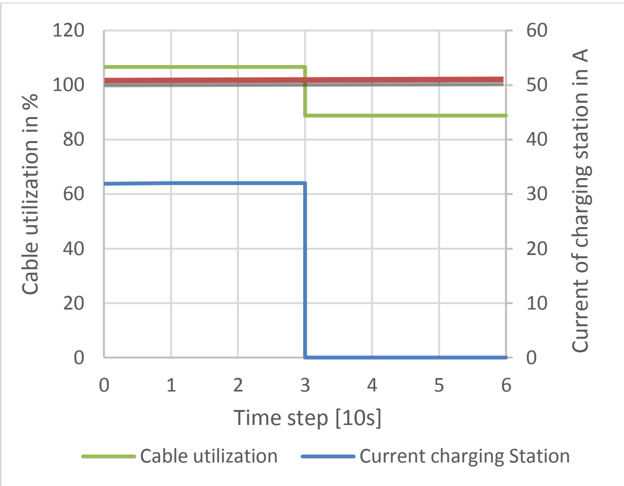

Figure 5: Measurements of cable and charging station

Figure 5 illustrates the cable utilization of the red colored cable in figure 4 and the current of one of the controlled charging stations. The threshold value for the cable overload is the normalized maximum thermal current of the cable. At the time step $t = 0$, the cable overload beyond 100% is detected and the grid state violation is observed for three cycles to avoid a premature control. After three cycles ($t = 2$), the CNP is started as described in the yellow phase. At the time step $t = 3$ one of the six charging stations was completely switched off by negotiation of the agents, with the result that the measured cable utilization falls below the threshold of 100%. The charging station was switched off completely, because the owner of the electric car has set a departure time the next day and the other electric vehicles had to leave much earlier. Although this control decision completely turns off a car, all local objectives of the Charging Station Agents are still fulfilled. The District Agent is not involved in the process of evaluating and developing possible set points for the charging station. The District Agent only receives the final set point offers from the charging station agents. In this way the problem can be reduced into very simple partial problems that can traced be more easily later. The second field test was performed after the sunset. The photovoltaic plant doesn't feed no longer into the distribution grid and all six charging stations load electric vehicles. This circumstances result in a lower voltage violation of the red colored nodes as shown in figure 6.

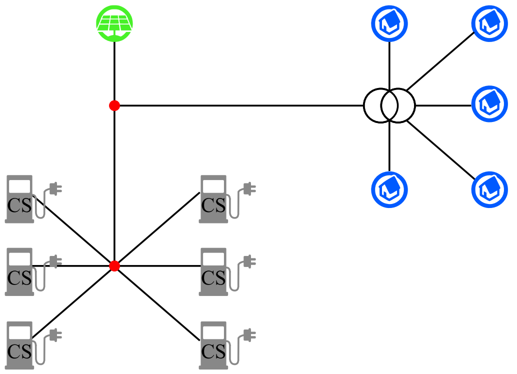

Figure 6: Second field test scenario: Lower Voltage Violation

It should be noted that the threshold for a lower voltage band violation was specially set at 226V. In reality, this voltage drop does not represent a real risk to the low voltage distribution grid. However, this threshold can be used well to examine the control action of the agents. Of course, an adjustable transformer could solve the problem, but the considered distribution grid only has a conventional transformer and therefore the control of the charging stations is the only option to solve the grid state violation. The following figure shows a cutout from the measurement series of the nodal voltage and the current of the controlled charging station.

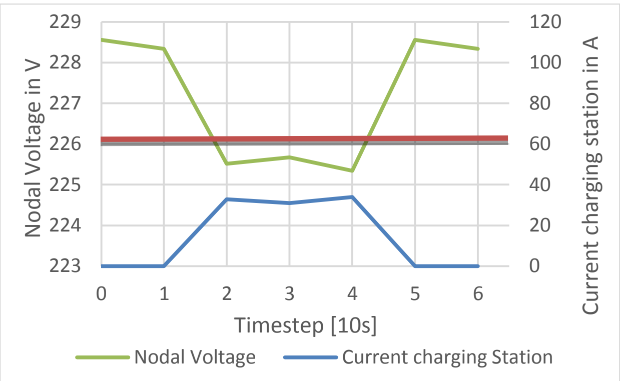

Figure 7: Second field test scenario: Lower Voltage Violation

The sixth charging station was manually switched on at the time step $t = 1$, which leads finally to a nodal voltage drop below the threshold value at the time step $t = 2$. After the already mentioned three cycles, the yellow traffic light phase and the CNP are started. The result of the agent-based control decision is mostly present after the time step $t = 4$. One of the charging stations is completely switched off and the critical grid state is solved. Finally, the grid state violation was fixed by a collective agent-based negotiation by fulfilling the local charging objectives of the charging station agents.

CRITICAL ANALYSIS OF THE APPROACH

In this chapter, the multi-agent-based control approach is compared to a centrally organized solution finding. The central mechanism develops the control solution on basis of the centrally collected information. In comparison, in the agent-based approach all necessary agents are used for solving the problem. Each agent has only its local objectives and model information and aggregates this information into higher valuable information for the interaction with other agents. This enables the use of more detailed information and models for finding a control decision. This aspect will become very interesting especially for distribution grids with a huge number of actuators. For a smaller number of actuators, the central approach can be advantageous. However, it must be considered that the integration of an additional actuator leads to a necessary modification of the central input parameters. The agent-based approach is more modular, because only partial agents can be modified, not the entire system. It should be mentioned that the number of industrial PCs is of course higher in the agent-based approach, because every deployed agent requires a target hardware. The distributed industrial PCs do not need the same high performance of a central PC, which allows to install "cheaper" low performance hardware. In summary, the agent-based approach is particularly suitable for large-scale distribution grids with many actuators that can be dynamically expanded.

CONCLUSION

Characteristic for this agent-based grid automation system is the distribution of the intelligence among several industrial PCs in the grid. This distributed intelligence was used to solve two different types of grid state violations by a collective development of an agent-based control decision. Each agent has only a limited view on the problem and can develop a suitable local control decision by inter agent communication and negotiation. In addition, the system has a high potential for flexibility and expandability in comparison to centralized SCADA systems. Nevertheless, the agent-based system can provide a solution with an increasing number of actuators, because the complete information content does not have to be evaluated by one computation unit. This increases the robustness of the system considerably. In Summary, this paper represents the essential experiences of an agent-based control under real conditions in the practical application in a low voltage distribution grid.

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