Smart Grid Architectures and the Multi-Agent System Paradigm

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***Abstract*—Currently, coal-, gas-, oil and nuclear power plants are used to meet the ever increasing energy demand. Nevertheless, due to an increasing environmental awareness and entailing regulations, energy prices rise considerably. As for today, many companies try to facilitate the production and utilization of much cheaper energy from renewable energy sources, such as wind and solar energy. However, due to constructional deficiencies, today grid infrastructures support only a small amount of renewable energy sources. To counter this problem, sophisticated control applications were designed, deciding on when and where to procure energy and safeguarding the stability of the entire grid architecture. Over the last years we have developed many smart grid applications and—due to the distributed nature of the problem solving task—we always applied multi-agent technology for this purpose. Java Intelligent Agent Component (JIAC), version five, innately provides many features indispensably required for smart grid applications. In this paper, we present our experiences in successfully using JIAC framework for the smart grid applications.**

Keywords*–*Power Network;Smart Grid;Distributed Power Generation; Electric Vehicles;Critical Infrastructures Protection;Demand and Response;Evolution Strategy; Multi-agent Systems;JIAC Agent Framework

I. INTRODUCTION

The world's energy demand increases continuously as the use of electronic devices grows. Increasing energy demand is accompanied by an ever increasing environmental awareness. 25.9% of total carbon emission is due to the consumption of high carbon fuels in current power industries [1]. In addition, today grid infrastructure is not able to cope with the increasing energy requirement. Aged components of current electric grid and out-dated technologies cause significantly inefficient and unstable electric systems. Beyond that, developing technology in last decades will change the methods and technics of generation and delivery of electricity. Integration of Information Communication Technologies (ICT) systems with grid infrastructure allows sophisticated control over generation, transportation, storage and consumption of electricity power. In current grid infrastructure, local distributed generators are accommodated on the electric grid in a fit-and-forget manner. Centralized electricity generation also creates an unreliable power load distribution system. Frequently, occurring blockages and outages inhibits sustainable power flow to the consumers.

Innovative techniques in smart grid will sustain utilization of electricity more securely and efficiently. Flexible and reorganisable virtual power plants ensure better management of power flow in case of any failures in electric grid. Assistance systems are developed in order to aid operators to handle with the problems. Managing charging and discharging processes of electrical vehicles (EVs) will be another significant issue. Uncontrolled charging profiles of EVs will increase the peak demands. Load management systems are developed to shift the EV demand to the other non-peak periods. Another concept, demand and response mechanism, makes the customers get involved into the power management. Considerable amount of savings can be achieved with demand management. Further, the demand and response concept allows customers to deliver surplus electricity to the power grid. In addition to that, policies for the reduction of CO_2 emission also become vital issues for future electric grid. According to the International Energy Agency (IEA) estimates, introduction of smart grid technologies will provide 0.9 to 2.2 gigatonnes reduction in CO_2 emissions by 2050 [1]. Over the last years, we have developed many smart grid applications and, due to the distributed nature of problems that were solved by with these applications, we always used multi-agent technology for this purpose. Nevertheless, agent-technology is still a domain which is mainly confined to the realm of research [2]. However, it is our experience that agent-technology should be seriously considered by industrial players. In order to substantiate this thesis, we present selected projects, in which we used agent technology, namely the JIAC agent framework [3]. It is our experience that most problems in smart grid architectures come from the distributed nature of the smart grid. The multi-agent system approach is a mature and efficient mechanism to master these problems.

The remainder of this paper is structured as follows: Current architecture of the electric grid and related challenges are described in section II. It is our purpose to emphasise the distributed nature of many grid related problems. In Section III, we outline smart grid architectures and potential extensions. In Section IV, we present selected applications that tackle smart grid related problems by using multi-agent technology. In Section V, we wrap up with a conclusion.

II. ELECTRIC GRID

An electric grid is an interconnected grid networks composed of several hardware and software components to distribute electricity from generation utilities to the end-users. Power delivery and communication infrastructures are two main layers of the electric grid.

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A. Current Grid Architecture and Challenges

Maintaining continuous stability in the electric grid is a great challenge since most of the consumed electricity is provided from centralized power plants. Supervisory Control and Data Acquisition (SCADA) systems are used for data transmission among electronic devices of the current electric grid. SCADA allows a utility's operators to monitor and control the conditions of the grid equipment and network processes. Computers at the control centre and Remote Terminal Units (RTU) in the field measure the data sets from hundreds to tens of thousands of data points [4]. Control model is based on slow automatic control by the control centre in order to balance load and generation. Synchronous Phasor Measurement Units (PMU) gathers data several times in each power cycle to get detailed picture of the grid dynamics for systems planning, control and post-incident analysis. Special Protection Schemes (SPS), which is also called as Remedial Action Schemes (RAS) have been developed to meet some of the wide-area control needs. An SPS involves instituting hardwired, point-to-point communication among substations [5]. In current infrastructure, these data can not be reasoned beyond the substations. Customers demand are not involved into the load management strategies. The present load management system is mostly oriented to the electricity generation of the traditional power plants. This grid structure has a limited ability to cope with fast cascading phenomena such as blockages and outages.

III. Innovative Smart Grid Concepts

Traditional electric grid has been evolving into the smart grid composed of spatially complex, intelligent and autonomous power and telecommunication networks. Renewables energy sources, plug-in electric vehicles and distributed battery systems will increase the reliability and stability of the electric grid. Intelligent power management system should be designed to manage the power load among various decentralized energy sources and consumers. In this sense, better understanding of the innovative concepts is vital to analyse and control new power system.

A. Electric Vehicles

Electric vehicles are regarded as dispatchable energy storage units. They become an integrated part of the power network with the well-known applications which are Vehicle-To-Grid (V2G) and Grid-To-Vehicle (G2V) technologies [6]. Co-operation of electric vehicles with renewable energy sources make the power network more secure and reliable. Required data regarding power quality and availability of Distributed Energy Resources (DERs) and EVs are aggregated and processed by responsible control units. There are several approaches to model charging and discharging processes of electric vehicles. The study [7] describes a decentralized online EV charging scheduling scheme as a cyber-physical system. In another approach [8], a strategy to coordinate the charging of plug-in EVs is prepared by using the non-cooperative games. In [9], a Threshold Admission with Greedy Scheduling (TAGS) algorithm is presented as a model of harging problem with admission control and charging capacities. This approach includes a reserve dispatch algorithm for compensating the intermittency of renewables. Integration of electric vehicles into power grid will also increase the peak demand. To decrease the demand in peak times, the load shifting methods are applied to the charging processes of electric vehicles.

B. Renewable Energy Sources

New smart grid concepts increase the efficiency of renewables, some of which are wind turbines, solar Photo-Voltaics (PVs) and biofuel cells. In Germany, renewable energy sources are expected to supply minimum 33% of the primary energy consumption by 2020 [10]. Centralized traditional power plants meet the power demand at the expense of high operation costs whereas renewable energy sources operate relatively at lower costs. Several studies are conducted to increase the efficiency of the grid operations of renewables. Different algorithms to predict the daily distribution of solar irradiation and hourly distribution of wind speed are compared in [11]. Performances of algorithms are compared and ranked to select the best suitable algorithm for renewable power management. Power shifting on demand side relying on generation of renewables provides high economic benefits for end-users. In addition to the cost benefits, renewable energy sources cut down high carbon emission, causing greenhouse effect.

C. Virtual Power Plants

Virtual Power Plant (VPP) refers to a diverse pool of wholesale renewable energy sources, electric vehicles and energy storage systems in supply side. According to the flexible power plant concept, numerous small-scale DER meet the power demands with sustainable power loads. VPPs are so modular that sources can be swapped in or out depending on the demands. The results of the study [12] shows that load reduction obtained with control schedules minimize the transmission congestion in the grid. In other words, flexibility of the VPP decreases the transmission congestion in distribution grid. In another study [13], an optimization algorithm is developed to manage a VPP composed of a large number of customers with thermostatically controlled appliances.

D. Micro Grids

In micro grids, distributed generation and storage units are tied together to the common feeder and this feeder is linked to the single point of common coupling, providing connection to the larger grid [14]. Micro grid concepts bring solutions to the several problems of the current electric grid. In case of any outages and blockages in utility grid, micro grids island from the utility grid and continue to serve for the power needs. In the event of any incidents, control system kills or activates the power stream according to the priority level of end users. Prioritized customers such as hospitals or telecommunication companies are fed with sustainable power load during the electricity interruption. Self-healing of micro grids increases considerably the reliability of the power grid. The control schemes required for operation of micro grid in grid-connected and islanded modes are studied in [15]. In micro grids, advanced power electronic systems control the operations and services among DER and surrounding Alternating Current (AC) electric system. The power electronic technology enables the micro grid operators to access smart meters and other intelligent field devices so that ancillary services are delivered to the electricity consumers. In this context, micro grids are regarded as autonomous sub-grids, providing its own power demands and related supportive services.

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E. Demand Response Management

Customers request power load with scheduling the operations of household appliances. Home energy management system enables end-users to participate in planning and scheduling the power management. Smart appliances are the integral components of the smart grid infrastructure. These intelligent household appliances are connected to the grid via smart meters which are electronically controlled interface devices. Smart meters have capability to receive and respond to the command signals coming from management systems of micro grids and utility grids. In doing so, demand side systems schedule the energy consumption of the electronic devices based the market prices and power capacity levels of supplies. Demand response mechanism encourages the energy consumers to shift the operations of the smart appliances from on-peak hours to off-peak hours. In [16], a heuristic is developed, allowing electricity demands to be shifted according to the dynamic energy market conditions.

F. Flexible Manufacturing System

Increasing energy costs and political policies on environmental precautions influence the methods of developing production plans. Achieving production targets and energy savings are two determinants for optimization of production plans. Several energy efficiency approaches are applied for the different manufacturing scenarios. In [17], the production plan achieving targets with minimum energy consumptions is chosen among alternative production plans. Process scheduling software determines the time slots, on which manufacturing processes use up the cheapest energy. While creating production plan, the scheduling software considers the physical constraints and interdependencies of the manufacturing processes. In advance of the implementation, the configuration of selected production plan can also be modified by the human operators. Overall, smart grid encourages the procurement of cheaper and less energy in the manufacturing industry.

G. Grid Management Model for JIAC Agent Implementations

New technologies arising in smart grid are integrated to the existing grid with innovative physical and cyber components [18]. Electric grid equipped with smart devices communicating with the control center enables efficient remote grid controlling and monitoring.

Smart metering system collects the energy data from smart meters and measured data are concentrated by smart grid data concentrators. Those collected data are unified by the central system called Meter Data Management (MDM) system. Some of end users in the grid are industrial companies, which plan manufacturing processes, or homeowners, who control their electricity consumption with use of home energy assistant systems. Data sets unified in central system are processed by the corresponding subsystems aiming at providing services for particular end users. Grid service providers in the proposed model are Residential Demand Management (RDM), Self- healing and Outage Management (SOM), Flexible Manufacturing Management (FMM), Electric Vehicle Charging/Discharging Management (EV - CDM) 1. The smart autonomous grid entities are represented as JIAC agents and these agents are scattered over the telecommunication network such as Local Area Network (LAN) and General Packet Radio Service (GPRS). Figure 1 shows the coordination of the smart meters and the smart grid data concentrators via Power Line Communications (PLC). JIAC agents, deployed on grid control devices, grid concentrators, and software components exchange JIAC messages by complex interaction protocols. Proposed grid management models include the control schemes and algorithms which are incorporated with intelligent agents. We will present smart grid applications based on JIAC agent framework in the next section.

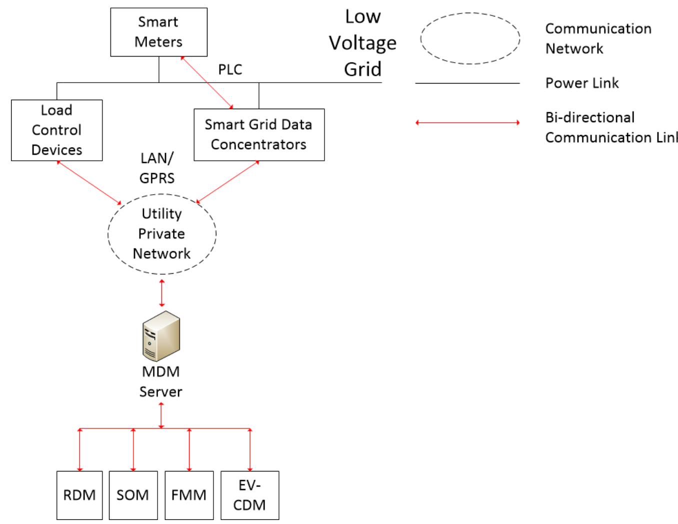

Figure 1. Structure of Grid Management Model

IV. JIAC AGENTS IN SMART GRID APPLICATIONS

In the previous section, we outlined challenges and possible (novel) areas of application that evolve from an ever increasing development of smart grid architectures. Over the last years, we developed several applications that fall under the umbrella of the one or the other category of evolving business concepts that we have outlined above.

It is our experience, that the multi-agent paradigm works very well for the smart grid domain, simply because of the distributed nature of most smart-grid-related problems. In this section, we present selected applications in more detail and respectively reference the categories (from the previous section), that our applications belong to. All applications that we present here are based on the JIAC agent framework [3]. JIAC agent framework is integrated with service-oriented paradigm. The framework provides the agent-platform, comprising agent nodes, physically distributed and it enables runtime environments for JIAC agents. JIAC agent multi-system can be defined by one or more spring configuration files. Runtime environment can be monitored and controlled by Java Management Extension Standard (JMX).

Our decision to use JIAC was based on a couple of factors. First, as most project were developed in an academic context, we required a free software framework. Furthermore, most applications were supposed to be executed in real life applications, thus, reliability and a comprehensive set of development tools and debugging capability was required as well. JIAC provides most of these features and had already been used in series of industrial applications [3]. For these reasons, we decided to use JIAC for our applications.

We proceed by presenting selected smart grid applications in more detail. In doing so, we respectively emphasize the distributed nature of the problem(s) that we tackled. The following presentations as well as additional project descriptions can be found in Lützenberger et al [19].

A. ILIas

The *Intelligente Lösungen zum Schutz vor Kaskadeneffekten in voneinander abhängigen kritischen Infrastrukturen* (ILIas) project [20] is based on the assumption that modern infrastructures are interdependent. Consider power- and telecommunications grids as examples for interdependent infrastructures. This interdependency may cause cascading effects in all involved infrastructures, whenever failures occur. ILIas aims to research and create intelligent and scalable management systems that provide prediction and reaction to cascading failure effects, so that actions to stabilize the managed infrastructure can be taken. Figure 2 presents the general architecture of the ILIas framework.

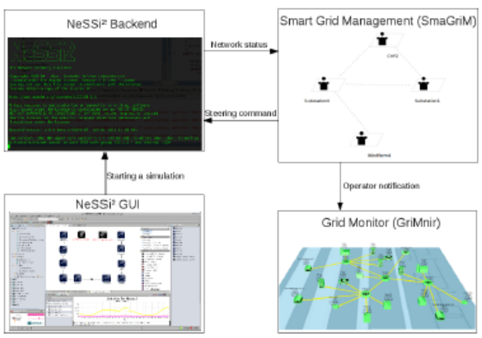

Figure 2. Overview over the ILIas Framework

An example for this is the reaction to power outages and the consequent failure of telecommunication networks in the affected areas. In ILIas, we developed an agent-based decentralized smart grid management system, which observes and controls the grid. Grid behaviour is predicted by means of simulation. Power and telecommunication networks are simulated by the agent-based simulation framework, Network Security Simulator, (NeSSi^2) [21].

NeSSi^2 is developed upon the JIAC framework, resulting in a distributed and easy-to-extend architecture. Detection algorithm plugins, traffic analysis, and automated attack generation are some of the capabilities, allowing for security research and evaluation purposes. We distinguish between an offline simulation, in which pre-defined scenarios are simulated, and an online simulation, in which the current grid state is used as a starting point for the calculation of predictions. The smart grid management is agent-based, such that JIAC agents in a Peer-to-Peer (P2P) network take over management duties for one smart grid entity. The distributed assembly allows our management system to work through partial or total power outages and to deal with sub-networks, which are either connected or independent from each other (islanded). We allowed our management agents to communicate with both physical as well as simulated smart grid entities. This design eases the testing—even the testing of large scale systems. Furthermore, we put particular emphasis on support for human operators.

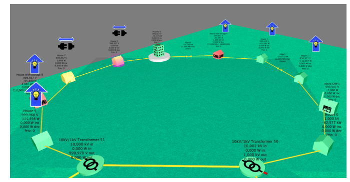

Figure 3. Smart grid live monitoring in ILIas (image detail)

Visualization is provided by our monitoring application (Figure 3), which shows the smart grid topology, live sensor data, the results of a situation analysis and action recommendations. The monitoring application can be used by human operators in order to check the current grid state and acknowledge or deny the recommended actions. Both, situation analysis and action recommendations are provided by the JIAC rule engine. Intelligent solutions developed in ILIas project provide electricity and telecommunication services to general public.

B. Gesteuertes Laden V2.0

The goal of Gesteuertes Laden V2.0 [22] was to use electric vehicles as mobile and distributed energy storages in order to increase the utilization of wind energy and to balance energy grids. The focus of our application was on the driver, such that mobility was ensured at all times. In order to account for this, we developed an application, which optimizes charging- and feeding processes of electric vehicles with respect to the driver's daily schedule. The application was implemented as a live system including real vehicles and charging stations.

The application [23] was designed as a distributed mobility and energy management system, in which relevant stakeholders (e.g., the driver, the vehicle manufacturer, the energy provider, the charging station, and the grid operator) were represented by JIAC Agents. The JIAC agents, distributed over the Gesteuertes Laden V2.0 architecture is shown in figure 4.

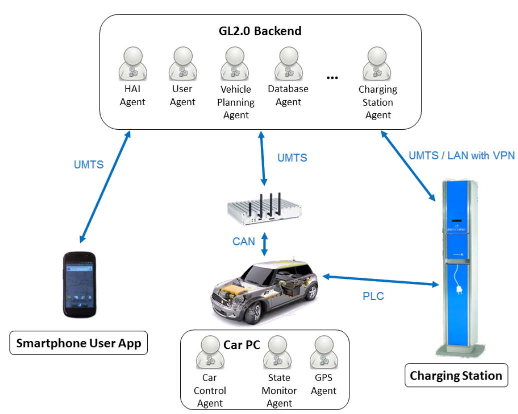

Figure 4. Architecture of Gesteuertes Laden V2.0

The system produces day schedules for the drivers. These schedules include journeys as well as charging- and feeding events [24]. In order to calculate these schedules, stakeholder-specific preferences and constraints had to be considered. Examples for such properties are: the driver's appointments, wind forecast, characteristics and current state of the electric vehicles, characteristics and availability of charging stations, and power grid constraints. In total, the system comprises twelve JIAC agents. These agents were permanently running on a back-end server and on the hardware of participating vehicles. In addition, more than 100 services were executed simultaneously, providing different functionality, from simple information services to complex planning algorithms. Beyond that, users and vehicles were represented by JIAC agents, which were deployed on the back-end server, taking the main responsibility for developing user- and vehicle schedules.

The data exchange between the electric vehicles and back-end agents was safeguarded by failover mechanisms in order to guarantee a reconnection after network-failures. Charging- and feeding events are triggered by the electric vehicle agents, which interact with the charging stations via power line communication. We also integrated external services, such as wind forecasts into our system. For this purpose, we used the *Web Service Gateway*, which is also provided by JIAC. An My Structured Query Language (MySQL) database was included as well. This connection was done with a generic database agent. We put particular emphasis on allowing users to participate in the scenario, thus, a smartphone application was developed. In order to connect this interface to the agent system, the *Human Agent Interface*, a JIAC component, was used. Finally, a monitoring component was installed to observe all agents and to notify developers in case services are down. The system was evaluated within a three-week field test [25]. To summarize, Gesteuertes Laden V2.0 brings in new approaches for integration of V2G to maximize the use of renewable energy for power grid stabilizaton.

C. The EnEffCo Project

In the Energy Efficiency Controlling (EnEffCo) project, we developed an optimization software [17, also [26]] that optimises production processes of the automotive industry in terms of energy costs. Optimization schema for production processes is illustrated in figure 5. The application uses the fact that (at least in Germany), industrial players are able to buy energy by means of short-term strategies at the day-ahead energy market. The prices at the day-ahead market are highly dynamic, thus, it is possible to minimize energy costs by shifting energy-consuming sub-processes to time slots with less expensive prices. Since contemporary production processes are highly complex and comprise many co-depending sub-processes, shifting parts of the overall process is not trivial.

We implemented our solution based on *Evolution Strategy* to produce reliable optimization results quickly. Entities were designed as JIAC agents, such that a server agent receives information about the production process in form of a bipartite graph. The graph contains architectural information, e.g., the sequential arrangement of all production steps, involved machinery and storages, but also meta information, such as the duration and the energy consumption of production steps. In addition, the server agent receives a production target, a timeframe and information on the energy price development. Based on this data, the initial production plan is generated (Figure 5). This initial plan is mutated, such that sub-processes are randomly shifted. Each server agent produces a defined number of mutations. Quality assessment is done by means of fitness function, which selects the most effective production plans. These plans are used as input for the next stage of evolution, where the production plans are mutated again. The process terminates whenever the quality of the best mutations remains steady across several generations.

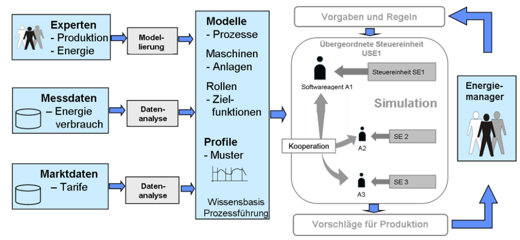

Figure 5. Energy Efficiency Controlling in the Automotive Industry

In addition to the server agent, we developed an optimization client (also a JIAC agent), which broadcasts an optimization problem by means of a custom protocol. Available server agents either accept and initiate the optimisation process or refuse as a result to different reasons. Results are sent back to the client, who compares available results and selects the best. The best production schedule is presented to the operator, who is able to configure his production line accordingly.

JIAC facilitated the development in two aspects. First, JIAC allows for the execution of several optimization agents in parallel. This capability can be used to counter the problem of stochastic optimisation algorithms to get stuck in local optima. It is our experience, that the simultaneous execution with different initial populations and random mutations increases the chance to overcome local maxima significantly. In doing so, the application's execution speed remains equal while the quality of the optimisation increases. The reason for this is that JIAC agents are truly multithreaded, capable of running on different Central Processing Units (CPUs). The second reason for the appliance of JIAC is the reliable communication of the agent framework. It is possible to distribute agents among different hosts and thus to increase the overall performance of the optimization software. As an example, complex optimisation scenarios can be supported by additional servers. These servers can be removed when this additional calculation performance is not required any more. The reason for this flexibility is the loose coupling between JIAC agents, which simplifies this process greatly and also supports maintenance issues. Erroneous or obsolete server agents can be replaced individually, without shutting down the entire application. To sum up, outcomes,which are gained from temporal shifting of energy demand support the manufacturing companies in the automative industry in terms of reducing energy consumption.

V. Conclusion

Smart grid architectures involve many autonomous systems with partial knowledge that have to communicate and cooperate in order to solve problems that each one of them for itself is not able to solve. It is difficult to provide a generic perspective on smart grid architectures, but in most applications that we developed, we designed energy consuming- and energy

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producing entities as agents. These agents represent relevant stakeholders that are capable to make decisions. We design these agents to pursue their goal to allocate required, or to dispose produced energy, respectively. To achieve this goal, agents communicate, cooperate, or negotiate and determine their actions themselves. Especially, in ILIas and Gesteuertes Laden 2.0, we had to account for aspects of data security. Furthermore, if one develops solutions for smart grid architectures, one has to deal with real distribution. As an example, consider the Gesteuertes Laden project, in which decision making software was deployed on electric vehicles, charging stations and backend servers. The main advantage to use agent technology for the implementation of these systems is the development support. Agent-oriented approaches for smart grid problems are modelled and implemented in described projects.

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