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Field Tests Applying Multi-Agent Technology for Distributed Control: Virtual Power Plants and Wind Energy

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Introduction

Multi-agent technology is state of the art ICT. It is not yet widely applied in power control systems. However, it has a large potential for bottom-up, distributed control of a network with large-scale renewable energy sources (RES) and distributed energy resources (DER) in future power systems. At least two major European R&D projects (MicroGrids [1] and CRISP [2]) have investigated its potential. Both grid-related as well as market-related applications have been studied. This paper will focus on two field tests, performed in the Netherlands, applying multi-agent control by means of the PowerMatcher [3] concept.

The first field test focuses on the application of multi-agent technology in a commercial setting, i.e. by reducing the need for balancing power in the case of intermittent energy sources, such as wind energy. In this case the flexibility is used of demand and supply of industrial and residential consumers and producers. Imbalance reduction rates of over 40% have been achieved applying the PowerMatcher, and with a proper portfolio even larger rates are expected.

In the second field test the multi-agent technology is used in the design and implementation of a virtual power plant (VPP). This VPP digitally connects a number of μ-CHP units, installed in residential dwellings, into a cluster that is controlled to reduce the local peak demand of the common low-voltage grid segment the μ-CHP units are connected to. In this way the VPP supports the local distribution system operator (DSO) to defer reinforcements in the grid infrastructure (substations and cables).

Integration of local demand and supply

Today a lot of attention goes towards demand response (DR) initiatives in which financial incentives are given to customers to curtail their energy use in periods with high energy prices at the wholesale market. Demand response can be seen as a next step in demand side management, that traditionally includes a variety of actions around load management and energy efficiency programs. With the growth of distributed generation DR is not only targeted at customer side demand, but also local supply is taken into account. Although DR involves the customer into competitive electricity markets, it can be seen from many field trials performed [4] that implementation is mainly based on price reactive models. We believe that multi-agent technology is the key towards a true integration of local supply and demand into electricity markets. Customers no longer only react to markets, but through their agents they become part of the market. Agents also are an enabling technology for active networks as promoted by the European SmartGrids technology Program.

A true integration of the supply and demand side in the electricity infrastructure requires new coordination technologies that are based on software agents for control of production and consumption units. Decisions are not taken at a central level, but are based on distributed, local intelligence and satisfy predefined optimisation criteria. These criteria may be aimed at increase of the share of distributed and renewable energy or accommodation of intermittent resources. Limiting conditions are security of supply, power quality and cost efficiency.

Multi-agent systems and control theory

Control theory deals with the behaviour of dynamical systems over time. The desired output of a system is called the reference variable. When one or more output variables of a system need to show certain behaviour over time, a controller tries to manipulate the inputs of the system (on the right in figure 1 denoted by "r") to realize this behaviour at the output of the system (denoted by "x - xset").

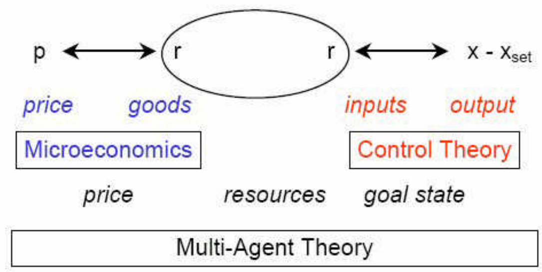

***Figure 1:** Microeconomics and control theory unified in multi–agent theory [5]*

In microeconomics a commodity is traded at a certain price. The price formation process is based on the value of the commodity in a market. If the microeconomic commodity (or goods) is associated with the inputs of a control system, as sketched on the left in figure 1, a control scheme arises, in which price formation is directly coupled to the system under control.

Consider an interactive society of a large number of agents, each of which has an individual control task. What kind of control strategies will interactively emerge from this agent society, and how good are these with respect to both local and global control performance criteria? Control theory and microeconomic theory are two, very different but both well-formalized, theories that can be brought to bear to this problem. The conceptual picture, then, is that agents are negotiating and trading with each other on a marketplace in order to acquire the resources that they need to achieve their individual control action goals.

Using multi-agent systems in an electronic market a Pareto effect emerges, i.e. the system optimizes on a global level, while at the local level the interests of all individual actors are optimally balanced against each other [5].

The PowerMatcher

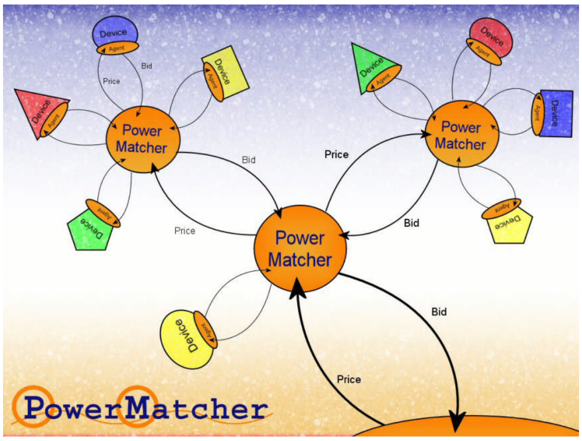

Figure 2: *PowerMatcher coordination infrastructure*

The PowerMatcher [3] is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption.

In the PowerMatcher model each device is represented by a control agent, which tries to operate the process associated with the device in an economical optimal way. The device agents mediate the electricity consumed or produced by the devices by using an electronic exchange market [6], [7].

The electronic market is implemented in a distributed manner via a hyper-linked structure of so-called PowerMatchers, as depicted in figure 2. A PowerMatcher matches demand and supply of a cluster of devices directly connected to it. Different types of devices can act as related consumers and producers. Each PowerMatcher receives an aggregated demand and supply curve from the devices connected, as well as from other PowerMatchers connected, and determines from it the equilibrium price, which is communicated back to the devices. From the market price and their own bid function each device agent can determine the power allocated to the device. PowerMatchers can themselves acts as an aggregate agent, bidding on other PowerMatchers, thus creating a flexible and scalable coordination infrastructure. A PowerMatcher cannot tell whether the devices connected to it are device agents or other PowerMatchers, since the communication interface of these are equal. Thus the concept is greatly scalable to include large numbers of device nodes.

The PowerMatcher control concept can be applied in several business cases. In this paper we discuss a number of results from two field tests performed in the Netherlands, and aimed at different goals. The first field test aims at reduction of imbalance in commercial portfolios containing distributed generators and responsive loads. The second one applies operation of distributed μ-CHP generators in a virtual power plant.

Field tests description

Field test 1: Imbalance reduction of intermittent wind

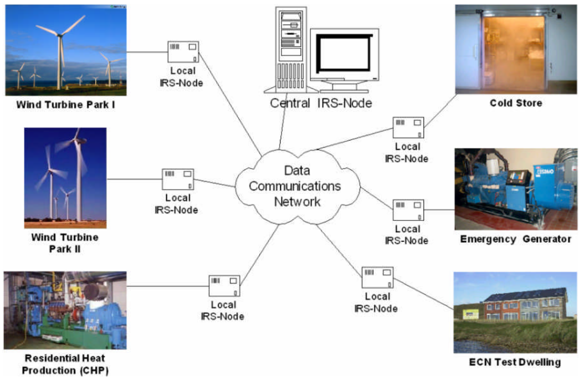

Figure 3: *Imbalance reduction system*

This field test, carried out with communicating energy devices located in different parts of The Netherlands, aims at automatically reducing the imbalance in the program of a commercial trader with wind power, by enhancing its program by additional, flexible, installations. Figure 3 shows the actual field-test configuration. On the supply side, the experiment includes two wind turbine parks, an emergency generator, and Combined Heat and Power (CHP) installations connected to a heat distribution network in a residential area. The demand side in the portfolio consists of controllable cooling loads in a meat-processing factory and a cluster of houses utilizing electric heat pumps. All control systems and one of the dwellings are actually connected in the field test, except for the final control of the installations, which is done only in the (research) dwelling. A simulation of installations, derived from models of the individual installation's processes, makes it possible to compare the agent-mediated control from the electronic power market with conventional control The capacity of the heat pump in the dwelling is negligible in comparison with the other installations. Therefore another 100 dwellings are simulated during the field test, each with its own individual behaviour. Using a wind prediction model and installation models of the different nodes in the field test, a day-ahead profile of the enhanced program is constructed [8].

The imbalance reduction field experiment is positioned in the Dutch imbalance market, so the imbalance market mechanism of the Dutch TSO is followed. For each balancing period of 15 minutes the day-ahead programs are compensated in real-time for over/under-realization by adapting the control strategy of the flexible installations, using agent algorithms operating on an electronic market via an ICT network.

Field test 2: A μ-CHP based virtual power plant

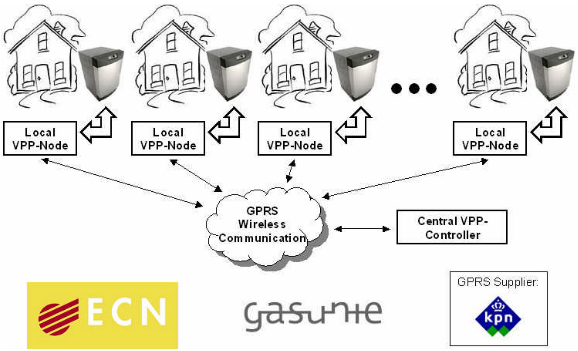

***Figure 4:** Virtual power plant control*

In the second field test the PowerMatcher forms the core of a μ-CHP based virtual power plant (VPP). In a cluster of up to 10 μ-CHP units each unit is represented by a control agent, which tries to operate the process associated with the device (residential space and tap water heating) in an economically optimal way. The control agent offers the electricity produced by the unit on an electronic exchange market. In this particular case the μ-CHP units are the producing devices and an LV substation is the only demander in the virtual market. During peak-periods the substation agent will place a bid on the virtual market for extra production. Through the internal VPP market mechanism, the μ-CHP units most able to react to this bid will start producing electricity. During off-peak periods the μ-CHP units anticipate by increasing their buffer capacity, due to absence of an incentive from the substation agent.

Field test results

LV substation simulation

A preliminary simulation study has been performed, in which a number of household devices have been simulated [3]. The households contain μ-CHP units, heat pumps, lighting, washing processes, all of them controlled by the PowerMatcher. The simulation shows the potential of reducing the power flow from higher voltage grid levels through the transformer to the low voltage grid level where the households are situated. The PowerMatcher electronic market yields a peak reduction of 30% from MV- to LV level. Moreover, it results in smaller fluctuations in local production / consumption, and a smoother profile of the external power import, as can be seen in figure 5.

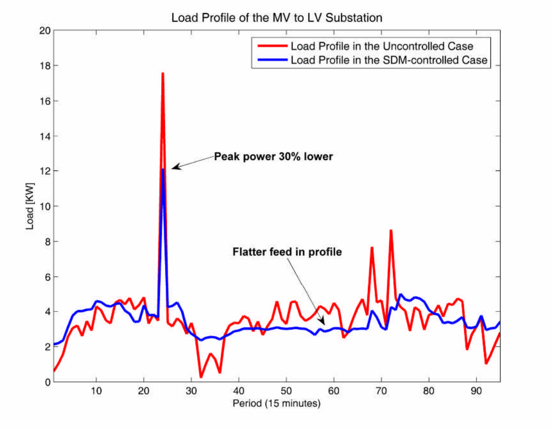

***Figure 5:** Load profile of the MV to LV substation*

The simulation provides evidence that supply-demand response strategies via local electronic markets are a promising mechanism for future ICT-supported power grids

Imbalance reduction for portfolio responsibility

Figure 6 shows the imbalance from the wind power (red) versus the resulting imbalance from the whole portfolio in the field test (blue). The blue line lies on the x-axis nearly 50% of the total period, meaning that a power balance has been established. The following phenomena are visible:

1. Underproduction of the wind turbine can only be partially compensated for. The portfolio imbalance (blue) is less than the wind power imbalance (red), but is not reduced to zero.

2. During some periods of underproduction the wind power shortage cannot be compensated for at all.

3. Some periods with large wind deviation can be compensated for completely in the cluster. The portfolio imbalance is zero.

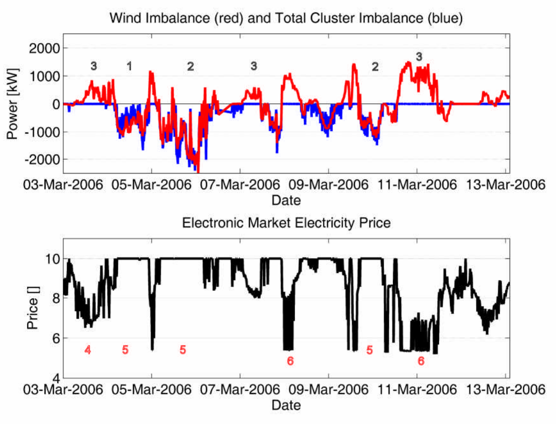

***Figure 6:** Imbalance reduction (above) and price fluctuations*

The same figure 6 also shows the development of the prices (black) according to the IRS market. An artificial price bandwidth of 5 €ct (minimum) and 10 €ct (maximum) is used. High prices show shortage of electricity in the portfolio (to be expected in case of underproduction of the wind turbine). Low prices show surplus.

4. Prices are fluctuating between minimum and maximum in periods that the portfolio is in balance. It demonstrates that the principle of market-based coordination works.

5. A period with maximum prices (10 €ct), results from the fact that the cluster of installations is unable to compensate completely for underproduction. A shortage remains.

6. Low prices (near 5 €ct) tend to occur in periods of large overproduction. Prices keep closer to 7-8 €ct for periods with smaller overproduction. In this case a gradual decrease of prices can be seen, indicating a gradual exhaustion of buffers in the portfolio.

The fact that underproduction of wind power cannot be compensated for in the portfolio is due to the cluster composition. The CHP installations in the cluster have a large capacity and thus could be expected to be able to compensate for underproduction of wind power. However, the CHP installations are scheduled to always be on in wintertime, so they can be turned off to avoid overproduction in the portfolio, but they do not provide extra capacity for compensation of underproduction. The production capacity of the emergency generator is too small to have more than a minor influence.

Virtual power plant control

Figure 7 shows the behaviour of the virtual power plant during a summer day. The day starts with a typical peak in total demand due to waking up. Immediately the price rises to its ceiling value and the μ-CHP units are triggered to switch on (based on tap water heating; no space heating will be required in summer). After a short period several boilers are filled and some of the μ-CHP units are switched off again. The peak reduction in the example is in the order of 15-20%. Note that the situation in the field test, shifting only the use of μ-CHP, is different from the simulation case, in which the PowerMatcher controls consuming installations as well.

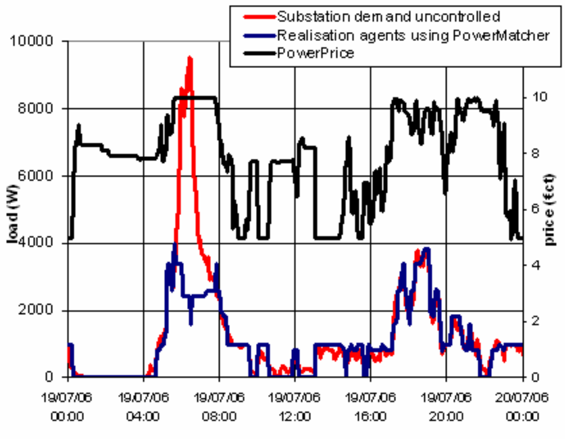

Figure 7: *VPP and substation load profiles versus established market prices*

In the afternoon the increase in substation load is totally taken care of by an increase in μ-CHP power supply. The market prices are near the maximum. During the day the market prices drop to a minimum level several times: apparently tap water heating is needed, despite the fact that there is no market incentive from the substation.

Note that during the winter, when the μ-CHP units are also producing heat for space heating, different patterns will arise.

Special topics

Local autonomy

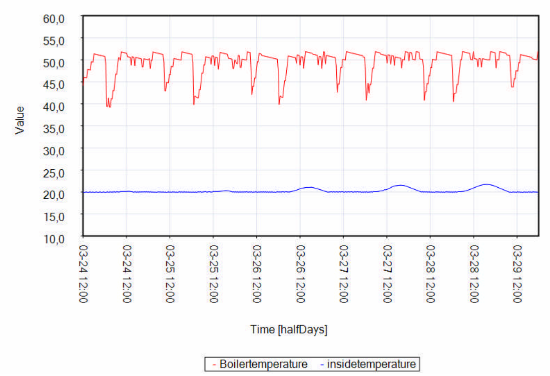

Figure 8: : *Conventional control: tap water temperature and room temperature*

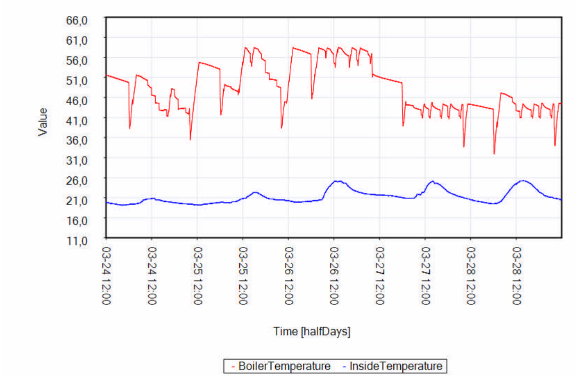

Figure 9: *Agent control: tap water temperature and room temperature*

The experiments performed show that local autonomy is feasible and agent systems are a good paradigm to guarantee this autonomy. Agents operating in an active network with market based algorithms lead to different control strategies than conventional schemes, but by no means they lead to inferior control. Figures 8 and 9 show the difference in strategy between conventional control of the tap water temperature, having the shape of a saw-tooth, and the agent control, shaped on the market outcome: if the market price goes up, the allocation and hence the tap water temperature goes down. While in the conventional control strategy after each usage dip the tap water temperature recovers to 50 °C, the agent strategy uses the flexibility in the temperature band between 40 °C and 55 °C.

Technical disturbances several times led to failure of the system, leading to unacceptably low temperatures in the dwelling. Therefore a backup control has been implemented: whenever the market fails, the agents assure that conventional backup control takes over.

Another aspect of local autonomy is the disclosure of local information through the agent communications. The PowerMatcher agents do not reveal any process information, except for a total requested load in the form of a bidding function. Nevertheless this information should remain confidential, not only to ensure a fair market, but also since load profiles may reveal residential absence.

Scalability

Due to their local intelligence agent systems have the advantage that the amount of communication towards a central supervisory system is drastically reduced.

Timing aspects

Communication speed is not essential for an IRS market. Communication through ADSL and UMTS did not lead to any performance or congestion problems. Programs, bids and allocations are communicated through short messages. Failure in the system, such as communication loss and malfunction of components, can disturb the market. It requires robust algorithms at the central node, although not every failure can be counteracted if no information is available about the reason of failure. For the experimental cluster market rounds of 15 minutes did not pose any problem. Even higher frequency markets (up to several minutes) are feasible.

ICT components

The field tests have been built using off-the-shelf computing and communication hardware. They have been used to interconnect and interface the cluster of power generation and consumption installations in a network using secure Internet-technology in an isolated branch of the public Internet, a virtual private network (VPN). On these computers, tools have been installed for data-collection, database storage and safe execution of novel control algorithms.

On-site connection to existing energy management systems has been made according to the design layout. OPC-Server proved to be a good mechanism to access industrial site installation data, without detailed knowledge about the installation control software.

Further research in active networks

The PowerMatcher development is part of ongoing research at the Energy research Centre of the Netherlands in the "Intelligent Energy Grids" program. The aim of the program is to facilitate future electricity grids with a large share of renewable and decentralised power supply. ICT will become an essential part of these grids. A transition towards a renewable energy infrastructure also requires a transition towards an active energy network for coordination of variable and decentralised energy flows. In this vision the research is supported by the European SmartGrids Technology Platform [9].

In active networks all connections, both producers and consumers, will play an active role in coordination and control of the network. Time and place of supply and demand will have inherent value that is used at new markets for electricity and system services for optimal control.

Active network control will have to lead to an increased stability in the network. Also scalability is required such that tens of thousands end even hundreds of thousands of network nodes can be integrated. The scalability applies to network architecture as well as coordination algorithms applied.

Control equipment needs downscaling, both in size and in cost. The goal is a low-cost control chip based on industrial standards, and that is built in devices at the production stage.

Conclusions

Various drivers push the production of electrical power in the current electricity infrastructure towards decentralization. Multi–agent technology and electronic markets form an appropriate technology to solve the resulting coordination problem. The PowerMatcher concept applied in this article in different field tests is a market–based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation, that provides other advantages as well, such as scalability and local autonomy.

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